

HEX **HEAT EXCHANGER** **DESIGN** **HANDBOOK**

5 **Physical** **properties**

VDI-Verlag GmbH

Verlag des Vereins Deutscher Ingenieure • Düsseldorf

● Hemisphere Publishing Corporation Washington New York London



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Heat Exchanger Design Handbook

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1 2 3 4 5 6 7 8 9 0 B C B C 8 9 8 7 6 5 4 3 2

This book was set in Press Roman by Hemisphere Publishing Corporation.

Editors: Brenda **Munz** Brienza, Judith B. Gandy, and Lynne Lackenbach.

Production supervisor: Miriam Gonzalez.

Compositors: Peggy M. Rote, Sandra F. Watts, Shirley J. **McNett**, and Wayne Hutchins.

BookCrafters, Inc., was printer and binder.

Distribution outside the U.S.A., Canada, Mexico, U.K., and Ireland, by VDI-Verlag, Dusseldorf.

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Library of Congress Cataloging in Publication Data

Main entry under title:

Heat exchanger design handbook.

Published under the auspices of the International Centre for Heat and Mass Transfer.

Kept up to date by supplements.

Includes bibliographies and indexes.

1. Heat exchangers-Design and **construction**—

Collected works. I. **Schlünder**, Ernst U. II. International Center for Heat and Mass Transfer.

TJ263.H38 1983 621.402 5 82-9267

ISBN 3-18-41-9085-4 (VDI Part 5) AACR2

ISBN 3-1841-9080-3 (VDI set)

ISBN O-89116-125-2 (Hemisphere set)

HEDH

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HEDH

GENERAL PREFACE

Ernst U. Schlünder

■ The idea to create a Heat Exchanger Design Handbook originated at the seminar Recent Developments in Heat Exchangers, organized by the International Centre for Heat and Mass Transfer (ICHMT) in Trogir, Yugoslavia in 1972.

Even though much heat transfer data and correlations were available, this information was scattered throughout the open literature or buried in the files of proprietary organizations. For manufacturers, vendors, and users of heat transfer equipment it was becoming more and more difficult not *only* to keep up with the continually growing heat transfer information but also to compare data and correlations from various sources. In addition, these sources were often inconsistent, and it was difficult for users to decide which data and correlations would serve their own purposes best. Moreover, over the years many heat transfer publications had become more analytical and more academic, which delayed their immediate application by practicing heat transfer engineers.

Because of this situation, a group of heat transfer specialists decided to collect heat transfer information available in the existing open literature and also-as far as possible-from proprietary sources in order to create a heat transfer information base. Recommended correlations based on selected experimental material would then be provided for all heat exchanger design data.

Although there was great enthusiasm for this project, not much progress was made until 1974, at the Fifth International Heat Transfer Conference in Tokyo. The idea was formulated then of publishing the information base under the auspices of the ICHMT by Hemisphere Publishing Corporation, the publisher of the

Centre. Eight representatives of universities, industry, and proprietary organizations formed the Editorial Board, which immediately started working on the scope and organization of this Handbook. As a result of these joint efforts the following five parts were planned:

Part 1 presents the theory of heat exchangers defining and explaining all parameters and concepts needed for thermal and hydraulic design and rating.

Part 2 contains recommended correlations for design and rating parameters based on evaluated available information. As far as possible experimental data are presented together with the recommended correlations in order to reveal both the consistency of the data as well as the reliability of the correlations.

Part 3 shows how to apply the material given in Parts 1 and 2 when solving actual heat exchanger design and rating problems. Because of the volume of material, it would be impossible for this part to cover all known kinds of heat exchangers. Nevertheless, most of the commonly used types of equipment are discussed in detail together with related installations such as cooling towers and combustion chambers.

Part 4 is devoted to the mechanical design of heat exchangers, which actually cannot be separated from thermal and hydraulic design. A useful comparison of some major national standards is included.

Part 5 contains physical property data that are needed in design calculations in the other four parts.

For each of the five parts, a member of the Editorial Board agreed to act as Lead Editor. Although each Lead Editor accepted additional administrative responsibility for his particular part, the whole Handbook has been a

cooperative effort with each editor sharing the reviewing and editorial work for all the material.

A large number of authors—well-known experts in their fields—have contributed to this Handbook. Each manuscript went through a review procedure and many of them were discussed during the regular meetings of the Editorial Board, which have been held every six months since 1975.

Nevertheless, this Handbook must be considered as a first step rather than as a final result. Though the concept was clear, the realization has not been easy and there is still room for improvement. Additionally, because new heat transfer data and correlations are published each year, a permanent updating procedure has been established to keep this Handbook current. This supplementary material will be offered regularly to the

subscribers. To ensure that any future material (including personal remarks and comments) can be added easily, a loose-leaf ring binder format was chosen for the Handbook.

The users of this Handbook are urged to communicate with us about what is missing and to make suggestions for improving the contents of the book and its applicability. This kind of interaction and cooperation between users and editors not only should improve the quality of the Handbook but also should stimulate further research work guided by the requirements of heat exchanger design.

The Editorial Board wishes to thank the publisher as well as the contributing authors for their most valuable cooperation.

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Preface

Geoffrey F. Hewitt

Almost all calculations of heat transfer require knowledge of one or more physical property parameters of the fluids and/or surfaces involved. It was this central importance of physical property information that led the Editors to decide to include a part of the Handbook dealing with such properties.

The importance of physical property data in heat, mass, and momentum transfer calculations makes it desirable for the heat transfer engineer to understand the fundamental physical nature of the parameters involved and their relation to other parameters, such as pressure and temperature. Thus, the first sections of Part 5 discuss the physical properties of various substances. This starts with a discussion of the properties of pure liquids and gases (Sec. 5.1). In many heat transfer applications, the fluids consist of mixtures of components and the next section (5.2) discusses the properties of such mixtures, including their thermodynamic equilibrium properties. In both **Secs.** 5.1 and 5.2, fluids were assumed to be Newtonian in behavior whereas, in fact, many practical fluids exhibit non-Newtonian characteristics. In practice, it is not normally useful to list **rheological** properties for non-Newtonian fluids since, from case to case, these fluids vary greatly. Thus, the emphasis is on measurement and (wherever possible) calculation of the properties and this topic is dealt with in detail in Sec. 5.3. The properties of solids are important in heat transfer calculations, not only in conductive heat transfer (where the thermal conductivity of the solid, its specific heat, and its density are important) but also in radiative heat transfer where surface emissivity is of critical significance. Of course, there are many publications on the physics and the calculation and measure-

ment of physical properties, and **Secs.** 5.1-5.4 are not intended in any way to replace these. Rather, an attempt is made to introduce the various parameters in a manner useful to the heat transfer engineer as a supplement to the tabulated values and as an aid in the utilization of the data in heat transfer calculations.

Perhaps the most widely used section of Part 5 will be Sec. 5.5 which presents tabulated data of the various physical properties. Here, the emphasis has been on the preparation of tables that will be directly useful to the heat transfer engineer. For instance, it is often assumed in engineering calculations of multiphase heat transfer that the system operates along the saturation line. Here, the tables of saturated properties (Sec. 5.5.1) will be particularly helpful in that they give **all** the liquid and gas properties needed for design together with the **interfacial** tension values. These tables have been developed especially for this Handbook. Many other new tables of data are also included.

As experience has shown, prediction and measurement techniques for physical properties are continuously improving. Thus, in common with other parts of the Handbook, this part on physical properties will, it is intended, evolve continuously with additional tabular material being added and revisions made of the introductory sections. The Editors would certainly appreciate (as was said in the General Preface) having advice from readers and users on any improvements or additions they would like to see in this material.

Finally, I would like to express my sincere thanks to the authors of this part for their endeavors in preparing the material and for their patience in making revisions to take account of the reviewers' comments.

NOMENCLATURE

■ The most frequently used symbols for quantities in heat and mass transfer are listed here according to the following principles:

1. Capital Roman letters (not italic) denote absolute quantities expressed in either **SI** basic units or derived units, e.g., $N = \text{kg m/s}^2$, $J = \text{N m}$, $W = \text{J/s}$.

Exceptions: Time (t), variables, coordinates (x, y, z, r), characteristic lengths in dimensionless numbers (l, d, s).

2. Lowercase Roman letters (not italic) denote the corresponding specific quantities per unit mass, mole, length, area, or volume (but not time). A dot over the symbol denotes an absolute or specific quantity per unit time.

Exception: Velocity (u, v, w).

A function will be indicated by $f(\cdot, \cdot)$.

Molar quantities are denoted by a tilde ($\sim$) over the symbol.

Exceptions: Gas constant ($\tilde{R}$), Loschmidt number ($\tilde{L}$), molecular weight ($\tilde{M}$), chemical potential (μ).

3. Lowercase Greek letters are used for coefficients and physical properties.

Exceptions: Overall heat transfer coefficient (U), heat capacity (c_p, c_v).

Capital Greek letters refer to eddy (turbulent) quantities; e.g., A denotes eddy thermal conductivity.

4. Dimensionless variables should be denoted by a superscript * following the corresponding symbol. e.g., y^* for a dimensionless coordinate.

5. Decimal fractions or multiples of the **SI** unit may be denoted by the corresponding symbol preceding the **SI** unit, e.g. $MW = 10^6 \text{ W}$.

Basic Quantities

Quantity	Symbol	Unit
Heat rate	$\dot{Q}$	W
Heat quantity	$Q = \int \dot{Q} dt$	J
Heat flux	$\dot{q} = \dot{Q}/A$	W/m ²
Time	t	s
Frequency	f	1/s
Mass	M	kg
Mass flow rate	$\dot{M}$	kg/s
Mass velocity (mass flow per unit area)	$\dot{m} = \dot{M}/S$	kg/m ² s
Mass flux	$\dot{m}_n = \dot{M}_n/A$	kg/m ² s
Number of moles	N	mol
Molar mass flow rate	$\dot{N}$	mol/s
Molar mass velocity	$\dot{n} = \dot{N}/S$	mol/m ² s
Molecular weight	$\tilde{M}$	g/mol
Density	ρ	kg/m ³
Concentration	c	kg/m ³
Molar density	$\tilde{\rho}$	mol/m ³
Molar concentration	$\tilde{c}$	mol/m ³
Mass fraction	x_i, y_i	kg _i /kg
Mass loading	X_i, Y_i	kg _i /kg _j
Molar mass fraction	$\tilde{x}_i, \tilde{y}_i$	mol _i /mol
Molar. mass loading	$\tilde{X}_i, \tilde{Y}_i$	mol _i /mol _j
Volume	V	m ³
Volume flow rate	$\dot{V}$	m ³ /s
Velocity	u, v, w	m/s
Surface area	A	m ²
Cross-sectional area	S	m ²
Length or diameter	L, D, l, d, s	m
Coordinate	$\psi, \varphi, r, x, y, z$	
Void fraction	ϵ	—
Fraction of volume flow rate	$\dot{\epsilon}$	—
Quality	x	—
Flow quality	$\dot{x}$	—
Work	W	J

Transport **coefficients**

Quantity	Symbol	Unit
Heat transfer coefficient	h	$\text{W/m}^2 \text{K}$
Mass transfer coefficient	β	m/s
Overall heat transfer coefficient	U	$\text{W/m}^2 \text{K}$
Drag coefficient	ξ	—
Friction factor	f	—
Emissivity	ϵ	—
View factor	φ_{12}	
Thermal conductivity	λ	W/m K
Diffusivity	δ	m^2/s
Kinematic viscosity	ν	m^2/s
Dynamic (absolute) viscosity	η	kg/m s
Thermal diffusivity	$\kappa \equiv \lambda/\rho c_p$	m^2/s
Surface tension	σ	N/m
Shear stress	τ	$\text{Pa (N/m}^2\text{)}$
Pressure	p	$\text{Pa (N/m}^2\text{)}$
Pressure drop	Δp	$\text{Pa (N/m}^2\text{)}$

Thermodynamic quantities

Quantity	Symbol*	unit
Enthalpy (specific)	h	J/kg
Internal energy (specific)	u	J/kg
Gibbs function free enthalpy (specific)	$g = h - T s$	J/kg
Free energy (specific)	$f = u - T s$	J/kg
Entropy (specific)	s	J/kg K
Chemical potential	μ	J/kg
Specific heat capacity	c_p, c_v	J/kg K
Temperature	T	$\text{K, } ^\circ\text{C}$
Mean logarithmic temperature difference	ΔT_{LM}	$\text{K, } ^\circ\text{C}$

*For totals, letters are capitalized, H, U.

Chemical reactions

Quantity	Symbol	Unit
Reaction enthalpy; phase-change enthalpy; latent heat	Ah	J/kg
Energy of activation	AE	J/kg
Equilibrium constant	K	Various
Rate constant	k	Various
Rate of reaction	$\dot{r}$	mol/m³s
Activity coefficient	γ_l	—
Fugacity coefficient	γ_g	—
Stoichiometric factors	ν_i	—

Physical constants

Quantity	Symbol	Unit
Gas constant	$\tilde{R}$	8.314 J/mol K
Loschmidt number	$\tilde{L}$	6.0252 · 10²³
Avogadro number	$\tilde{L}$	1/mol
Stefan-Boltzmann constant	C_s	5.6697 · 10⁻⁸ W/m²K⁴
Acceleration of gravity	g	m/s ²
Standard acceleration of gravity	$g_n = 9.8 \dots$	m/s ²

Subscripts

Quantity	Symbol
Wall	w
Bulk	b
Mean	m
Solid	s
Liquid	l
Gas	g
Inlet	in
Outlet	out

Dimensionless numbers (most frequently used)

Name	Symbol and definition
Archimedes number	$Ar = gl^3 \Delta \rho / \nu^2 \rho = gl^3 \rho \Delta \rho / \eta^2$
Biot number	$Bi = \alpha_g l / \lambda_s$ or $\alpha_l l / \lambda_s$
Effectiveness	E
Euler number	$Eu = \Delta p / (\rho u^2 / 2)$
Fourier number	$Fo = \kappa t / l^2 = \lambda t / \rho c_p l^2$
Froude number	$Fr = u^2 / gl$
Galileo number	$Ga = l^3 g / \nu^2 = l^3 g \rho^2 / \eta^2$
Grashof number	$Gr = gl^3 \Delta \rho / \nu^2 \rho = gl^3 \rho \Delta \rho / \eta^2$
Graetz number	$Gz = u d^2 / \kappa l = u d^2 \rho c_p / \lambda l = Re Pr d / l$
Knudsen number	$Kn = l_0 / l$, where l_0 is the molecular mean free path
Lewis number	$Le = \kappa / \delta = \lambda / \rho c_p \delta$
Mach number	$Ma = u / u_{\text{sound}}$
Number of transfer units	NTU
Nusselt number	$Nu = \alpha l / \lambda$
Péclet number	$Pe = ul / \kappa = ul \rho c_p / \lambda = Re Pr$
Phase change number	$Ph = c_p \Delta T / \Delta h_{gi}$
Prandtl number	$Pr = \nu / \kappa = \eta c_p / \lambda$
Rayleigh number	$Ra = Gr Pr$
Reynolds number	$Re = ul / \nu = ul \rho / \eta = \dot{m} l / \eta$
Schmidt number	$SC = \nu / \delta = \eta / \rho \delta$
Sherwood number	$Sh = \beta l / \delta$
Stanton number	$St = \alpha / \rho u c_p = Nu / Re Pr$
Strouhal number	$Sr = fl / u$
Weber number	$We = u^2 \rho l / \sigma$

Dimensionless mass transfer numbers are distinguished from dimensionless heat transfer numbers by a prime ('), e.g., $Bi' = \beta l / \delta$. Exceptions: $Nu' = \beta l / \delta = Sh$ and $Pr' = \nu / \delta = SC$

HEDH

INTERNATIONAL SYSTEM OF UNITS (SI): RULES, PRACTICES, AND CONVERSION CHARTS

J. Taborek

■ HEDH is written in **SI** units because this system has been officially adopted by all countries and is replacing the older metric engineering system, the cgs system, as well as the U.S. customary system. In this section we shall review the basic rules for use of the SI. However, recognizing the fact that many references are written in other unit systems, comprehensive unit conversion charts are included.

A. Basic SI units

SI is absolute in the sense that there are only seven fundamental, precisely defined basic units from which all others are derived. The following five units are important to heat transfer and fluid flow.

length (meter, m): defined in terms of krypton-g6 wavelength

mass (kilogram, kg): the mass of an international prototype, approximately equal to the weight of 1 liter H_2O at $4^\circ C$

time (second, s): defined in terms of radiation frequency of the cesium-133 atom

temperature (kelvin, K): defined in terms of the triple point of water (ice point = $273.15 K$)

amount of substance (mole, mol): amount of substance that contains as many elementary entities as there are atoms in 0.012 kg of carbon-12. The elementary entities must be identified when the mole is used (atoms, molecules, ions).

B. Derived SI units with special names

Because **SI** is defined by the basic units only, there is a need for establishing definitions for the most frequently used composite or derived units, mainly for the purpose of simplifying unit notation. Thus, for example, newton, N, replaces $kg\ m/s^2$.

There are a number of derived units that have special names, signifying their importance: newton, joule, watt, **pascal**, and many others. While the unit symbols are capital letters (N, J, W, Pa), the spelled out unit names begin with lowercase letters, that is, newton, joule, watt, and **pascal**.

The most frequently used derived **SI** units with special names in the area of heat transfer and fluid flow are shown in Table 1.

Table 1 Most frequently used derived SI units

Quantity	Unit	Symbol	Dimension
Force	newton	N	$kg\ m/s^2$
Energy, work, heat (also power X time)	joule	J	$N\ m$ or $kg\ m^2/s^2$ $W\ s = J\ s/s$
Power	watt	W	$J/s = kg\ m^2/s^3$
Pressure	pascal	Pa	$N/m^2 = kg/m\ s^2$
Frequency	hertz	Hz	$1/s$
Dynamic viscosity	poise centipoise	P cP	$0.1\ Pa\ s$ mPa s

C. Prefixes and specification rules

The magnitude of the basic units may often not fit the practice of specific applications without using a large number of decimal digits or power of ten multipliers. **SI** provides for this by assigning prefixes to the basic units, as shown in Table 2.

Thus, for example, to express very high pressures (stresses) in Pa, the megapascal, **MPa**, is used instead of 10^6 Pa. The preferred graduation is in powers of 10^3 , and there are only a few exceptions to this rule, such as for units that are deeply ingrained in common use, such as centimeter. Some of these are discussed later.

(a) Punctuation and spelling rules

The following general rules should be carefully followed to maintain **SI** consistency.

1. **Prefixes** are attached directly to the base unit symbol or a derived unit symbol with a special name, such as km for kilometer or MW for megawatt.

2. Prefixed units are spelled out in text as one word, without hyphen, such as meganewton, not **mega-newton**.

3. The multiplication of base units can be expressed by leaving a space between the symbols, such as N s for newton X second. However, for better clarity, a center dot is often used, for example, N·s. This usage becomes especially important when the symbol m is used, which can stand for **milli** or for meter. Thus **mN** (millinewton) is clearly distinguished from **m·N** (meter X newton).

4. A prefix applied to a base unit constitutes a new unit. When a power is applied to such a unit, the exponent operates on the **prefixed** unit as an entity, i.e., $\text{mm}^2 = (\text{mm})^2$.

5. The unit of length in **SI** is correctly spelled “**metre**” (French spelling). This rule will be hard to enforce in U.S. literature, however, and meter will probably be more commonly used.

Table 2 **SI** prefixes

Factor	Prefix	Symbol	Status
10^{12}	tera	T	Preferred
10^9	giga	G	Preferred
10^6	mega	M	Preferred
10^3	kilo	k	Preferred
10^2	hecto	h	Accepted
10	deka	da	Accepted
10^{-1}	deci	d	Accepted
10^{-2}	centi	c	Accepted
10^{-3}	milli	m	Preferred
10^{-6}	micro	μ	Preferred
10^{-9}	nano	n	Preferred
10^{-12}	pico	p	Preferred

6. Multiple **prefixes** are prohibited. This presents some problems with the unit kilogram (kg), where the k stands for the **prefix** kilo and is one of the very few inconsistencies in **SI** (a carryover from the older cgs system). Thus k (for kilo) cannot be used in connection with kg, as this would result in the unacceptable term kkg. Equally incorrect is the use of Mg (megagram), as gram is not a basic **SI** unit. Thus, the unit used is 10^3 kg or the equivalent unit, metric ton (see below).

Similarly, mkg is not an acceptable way to express 10^{-3} kg, and the more common alternate unit of gram (g) is used.

D. Alternate units and supplementary comments

There are as many derived units as the technology demands, as **SI** is particularly suitable for this purpose by the clearly defined unit relations. The Nomenclature of this handbook contains practically all such units used in heat transfer and fluid flow, showing the appropriate **SI** dimensions. Consequently, these are not repeated here.

In some cases, strict **SI** rules are relaxed to respect generally accepted and deeply established practices. The following list presents most frequently used exceptions, together with some additional comments to alternate units, their definition, and their usage.

length: The unit centimeter (cm) is a very practical measure for everyday usage (person's height, $6 \text{ ft} \approx 183 \text{ cm}$), and will probably remain in perpetual use.

mass: The unit of kilogram is often too small for expressing quantities of mass experienced in many engineering applications. One of the few weaknesses of **SI** is the lack of a well-defined alternate unit of mass. As explained above, the prefixed units (kkg, Mg) are not acceptable. Instead, an alternate unit for large quantities of mass is introduced, designated metric ton (symbol **t**), $t = 1\,000 \text{ kg}$. While this unit has not yet been accepted as a recognized **SI** unit, it is very much in common use.

In the U.S. customary lb.-based system, several definitions of a unit of mass similar in magnitude to the metric ton exist. In engineering practice, the following two definitions of the lb.-based ton are most frequently used:

short ton, which is equal to 2 000 lb,
(exact) and therefore approximately = 907.2 kg
long ton, which is equal to 2 240 lb,
(exact), and therefore approximately = 1 016 kg

It is important to be aware of these differences in the inconsistently defined U.S. customary system.

For small quantities of mass, gram (g) is also often used in place of 10^{-3} kg.

time: The unit second (s) should be used whenever possible, as the alternates of minutes, hours, and days are nondecimal entities, and thus complicate the system.

However, to express large quantities of mass per unit of time, the unit hour (h), 3 600 seconds, or the unit day (d), 86 400 seconds, must be used sometimes. The time unit minute (min), often used in the U.S. customary system (**gal/min**), has no real justification, except that it is ingrained in some industrial practices. Otherwise, the differential quantity of a minute, as compared to a second, can be readily expressed by **prefixes** in SI units, to obtain a number with reasonable digits.

force: The newton is a very small unit of force, approximately equal to the weight of water in a small glass. Thus the more practical units of force are often the **kN** or **MN**.

volume: The liter, defined as dm^3 , is a very popular unit of volume for everyday use, such as for water and gasoline. Liter (L) is accepted as a common alternate unit.

amount of substance: The frequently used units of the metric engineering system, gram-mol and kg-mol, are designated in SI as follows: 1 gram-mol = 1 mol (SI), and 1 kg-mol = 1 kmol (SI). Thus 1 mol = 6.023×10^{23} molecules.

pressure: The basic unit of pressure, **pascal** ($\text{Pa} = \text{N/m}^2$), is a very small quantity, equal to the pressure exerted by about 0.1-mm layer of water over 1 m^2 . Thus in most engineering applications **kPa** or **MPa** is more useful.

Many derived units of pressure are firmly established in various branches of engineering and will probably remain in use indefinitely. The most important metric-based units are:

bar: has exact relationship to SI ($=100 \text{ kPa}$)

torr = **1 mmHg** = 0.133 **kPa**: used for gas pressure measurements

mm water = 9.8067 Pa: used for very small gas pressure measurements

at (technical atmosphere) = $\text{kgf/cm}^2 = 98.066 \text{ kPa}$

atm (normal or barometric atmosphere) = 760 mmHg = 101.3 **kPa**

temperature: In many engineering applications it is more convenient to use degrees Celsius rather than the absolute unit kelvin. The use of Celsius is permitted as an alternate, with the relationship

$$T(^{\circ}\text{C}) = T(\text{K}) - 273.16 \text{ and } \Delta T(^{\circ}\text{C}) = \Delta T(^{\circ}\text{K})$$

Table 3 Unit conversion

Physical quantity	Given in G i v e s	Multiplied by Divided by	Gives Given in	Approximate or useful relationship
Length	ft	0.3048	m	$3\frac{1}{4} \text{ ft} \approx 1 \text{ m}$
	in	25.4 (exact)	mm	$1 \text{ in} \approx 25 \text{ mm}$
	mil	0.0254	mm	
	yard	0.9144	m	
	mile (mi)	1 609.3	m	$1 \text{ mi} \approx 1.6 \text{ km}$
	km	0.621388	mi	
Area	ft^2	0.092903	m^2	$100 \text{ ft}^2 \approx 9 \text{ m}^2$
	in	645.16	mm^2	$1 \text{ in}^2 \approx 650 \text{ mm}^2$
	acre	4 047.0	m^2	
Volume	ft^3	0.028317	m^3	$35 \text{ ft}^3 \approx 1 \text{ m}^3$
	U.S. gal	0.003785	m^3	$260 \text{ gal} \approx 1 \text{ m}^3$
	U.S. gal	3.785	liter (L)	$1 \text{ gal} \approx 3\frac{3}{4} \text{ L}$
	L (liter)	0.2642	U.S. gal	$1 \text{ L} \approx 0.26 \text{ gal}$
	Brit. gal	0.004546	m^3	
	U.S. gal	0.13368	ft^3	
	barrel (U.S. pet.)	0.15898	m^3	
	barrel (U.S. pet.)	42	U.S. gal	
Velocity	ft/s^a	0.3048	m/s	$10 \text{ ft/s} \approx 3 \text{ m/s}$
	m/s	3.2808	ft/s	
	ft/min	0.00508	m/s	$100 \text{ ft/min} \approx 0.5 \text{ m/s}$
	mi/h	1.6093	km/h	$30 \text{ mi/h} \approx 48 \text{ km/h}$
	km/h	0.6214	mi/h	$50 \text{ km/h} \approx 31 \text{ mi/h}$
	knots	1.852	km/h	

(See footnotes on page xxix.)

Table 3 Unit conversion (Continued)

Physical quantity	Given in Gives	Multiplied by Divided by	Gives Given in	Approximate or useful relationship
Mass	lb_m kg metric ton ton (2 000 lb.)	0.45359 2.2046 2 204.6 907.18	kg lb_m lb_m kg	1 lb_m $\approx$.45 kg 1 kg $\approx$ 2.2 lb, metric ton = 10 ³ kg
Force	lb_f lb_f kg_f kg_f dyne	4.44822 0.45359 2.2046 9.80665 0.00001 (exact)	N = kg m/s ² kg_f lb_f N N	1 N $\approx$ 0.1 kg_f $\approx$ 0.22 lb_f
Amount of substance	lb_m-mol g-mol kg-mol mol	453.6 1.000 1.000 1 000	kmol mol kmol kmol	
Mass flow rate	lb_m/h kg/s lb_m/s lb_m/min	0.000 1260 7 936.51 0.45 36 0.00756	kg/s lb_m/h kg/s kg/s	10 ³ lb/h = .13 kg/s
Volume flow rate	U.S. gal/min U.S. bbl/day U.S. bbl/day ft³/s ft³/min	6.309 $\times 10^{-5}$ 0.15899 1.84 $\times 10^{-6}$ 0.02832 0.000472	m³/s m³/day m³/s m³/s m³/s	
Mass velocity (mass flux)	lb_m/h ft² kg/s m²	1.356 $\times 10^{-3}$ 131.5	kg/s m² lb_m/h ft²	
Energy (work) (heat)	Btu^b Btu Btu kcal ft lb_f Wh	1 055.056 0.2520 778.28 4 186.8 1.3558 3 600	J = N m = W s kcal ft lb_f J J J	1 Btu $\approx$ 1 000 J 1 kcal $\approx$ 4 Btu 1 kcal $\approx$ 4 000 J
Power	Btu/h W kcal/h ft lb_f/s hp (metric) Btu/h tons refriger.	0.2931 3.4118 1.163 1.3558 735.5 0.2520 3 516.9	W = J/s Btu/h W W W kcal/h W	10 ⁶ Btu/h $\approx$ 300 kW 1 000 kW $\approx$ 3.5 $\times 10^6$ Btu/h
Heat flux	Btu/h ft² W/m² kcal/cm² s	3.1546 0.317 41.868	W/m² Btu/h ft² W/m²	1 000 Btu/h ft ² $\approx$ 3.2 kW/m ²
Heat transfer coefficient	Btu/h ft² °F W/m² K kcal/cm² s °C	5.6784 0.1761 41.868	W/m² K Btu/h ft² °F W/m² K	1 000 Btu/h ft ² °F $\approx$ 5 600 W/m ² K
Heat transfer resistance	(Btu/h ft² °F)⁻¹ (W/m² K)⁻¹	0.1761 5.6784	(W/m² K)⁻¹ (Btu/h ft² °F)⁻¹	0.001 (Btu/h ft ² °F) ⁻¹ $\approx$ 0.000 18 (W/m ² K) ⁻¹
Pressure	lb_f/in² (psi) kPa bar	6.8948 0.1450 100	kN/m² = kPa psi kPa	1 psi $\approx$ 7 kPa 14.5 psi $\approx$ 100 kPa

(See footnotes on page xxix.)

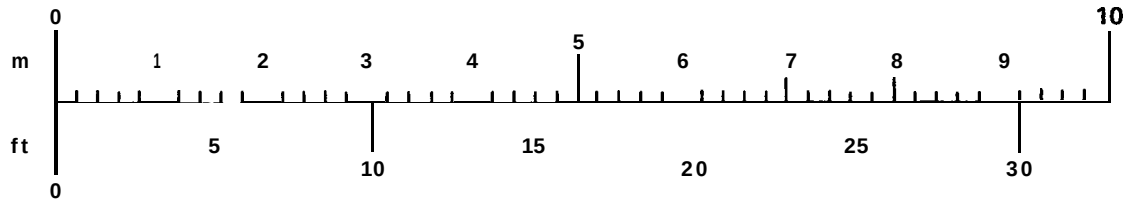
Table 3 Unit conversion (Continued)

Physical quantity	Given in Gives	Multiplied by Divided by	Gives Given in	Approximate or useful relationship
Pressure (Continued)	lb_f/ft² mm Hg (torr) in Hg mm H ₂ O in H ₂ O at (kg _f /cm ²) atm (normal)	0.0479 0.1333 3.3866 9.8067 249.09 98.0665 101.325	kPa kPa kPa Pa Pa kPa kPa	1000 kPa = 1 MPa ≈ 150 psi 1 in H ₂ O ≈ .25 kPa atm = 760 mmHg
Mass flux	lb_m/ft² s lb_m/ft² h	4.8824 0.001356	kg/m ² s kg/m ² s	
Physical and Transport Properties				
Thermal conductivity	Btu/ft h °F W/m K kcal/m h °C	1.7308 0.5778 1.163	W/m K Btu/ft h °F W/m K	steel ≈ 50 W/m K water (20° C) ≈ 0.6 W/m K air (STP) ≈ 24 mW/m K
Density	lb_m/ft³ kg/m ³ lb _m /U.S. gal	16.0185 0.06243 119.7	kg/m³ lb_m/ft³ kg/m ³	62.4 lb _m /ft ³ ≈ 1 000 kg/m ³
Specific heat capacity	Btu/lb_m °F kcal/kg °C	4 186.8 4 186.8	J/kg K J/kg K	1 Btu/lb _m °F ≈ 4.2 kJ/kg K
Enthalpy	Btu/lb_m kcal/kg_m	2 326 4 186.8	J / k J / k	
Dynamic (absolute) viscosity	centipoise (cP) poise (P) cP cP lb _m /ft h lb _m /ft h cP lb _m /ft s	0.001 0.1 1.000 1 000 0.0004 134 0.4134 2.4189 1.4482	kg/m s Pa s mPa s μPa s Pa s cP lb_m/ft h Pa s	kg/m s = N s/m ² = Pa s water (100°C), 0.31 cP air (1 00°C), 0.021 cP
Kinematic viscosity	stoke (St), cm ² s centistoke (cSt) ft ² Is	0.000 1 10 ⁻⁶ 0.092903	m ² /s m ² /s m ² /s	
Diffusivity	ft ² /s	0.092903	m ² /s	
Thermal diffusivity	m ² /h ft ² /s ft ² /h	0.0002778 0.092903 25.81 × 10 ⁻⁶	m ² /s m ² /s m ² /s	
Surface tension	dyne/cm dyne/cm lb _f /ft	0.00 1 6.852 × 10 ⁻⁵ 14.954	N/m lb_f/ft N/m	
Temperature relations:	°C = $\frac{5}{9} [°F - 32]$ °F = $\frac{9}{5} (°C) + 32$	°C = (°F + 40) $\frac{5}{9}$ - 40 °F = (°C + 40) $\frac{9}{5}$ - 40	$\Delta T (°C) = \frac{9}{5} \Delta T (°F)$ $\Delta T (°F) = \frac{5}{9} \Delta T (°C)$	K = °C + 273.15 R = °F + 459.67
Miscellaneous:	Acceleration of gravity (standard): Gas constant: Stefan-Boltzmann constant:	g = 9.806 65 m/s ² R = 8 314.3 m N/K kmol 5.669 7 × 10 ⁻⁸ W/m ² K ⁴ 1.714 × 10 ⁻⁹ Btu/ft ² h R ⁴		

^a Even though the abbreviations s and h were introduced only with the SI, they are used here throughout for consistency.

^b Note: the calorie and Btu are based on the International Standard Table values. The thermochemical calorie equals 4.184 J (exact) and is used in some older texts.

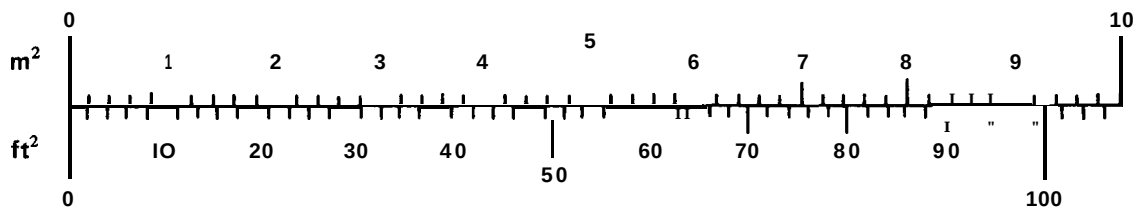
LENGTH: meter, m; foot, ft



$$\text{m} \times 3.2803 = \text{ft}$$

$$\text{ft} \times 0.3048 = \text{m}$$

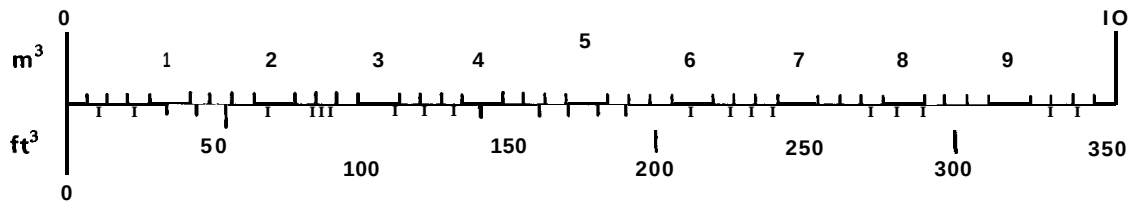
AREA: square meter, m^2 ; square foot, ft^2



$$\text{m}^2 \times 10.764 = \text{ft}^2$$

$$\text{ft}^2 \times 0.0929 = \text{m}^2$$

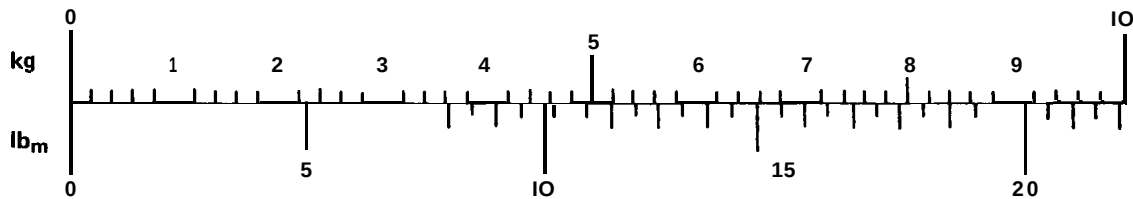
VOLUME: cubic meter, m^3 ; cubic foot, ft^3



$$\text{m}^3 \times 35.314 = \text{ft}^3$$

$$\text{ft}^3 \times 0.0283 = \text{m}^3$$

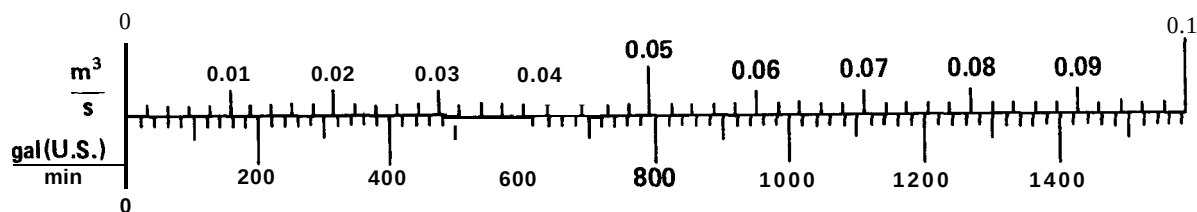
MASS: kilogram, kg; pound-mass, lb,



$$\text{kg} \times 2.205 = \text{lb}_m$$

$$\text{lb}_m \times 0.454 = \text{kg}$$

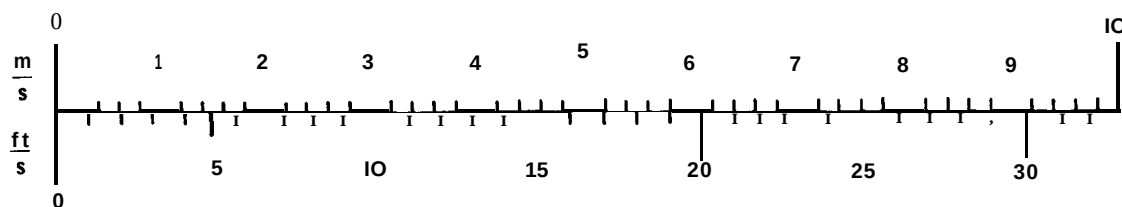
VOLUME FLOW RATE: $\frac{\text{m}^3}{\text{s}}$; $\frac{\text{gal(U.S.)}}{\text{min}}$



$$\frac{\text{m}^3}{\text{s}} \times 1.585(10^4) = \frac{\text{gal(U.S.)}}{\text{min}}$$

$$\frac{\text{gal(U.S.)}}{\text{min}} \times 6.31(10^{-5}) = \frac{\text{m}^3}{\text{s}}$$

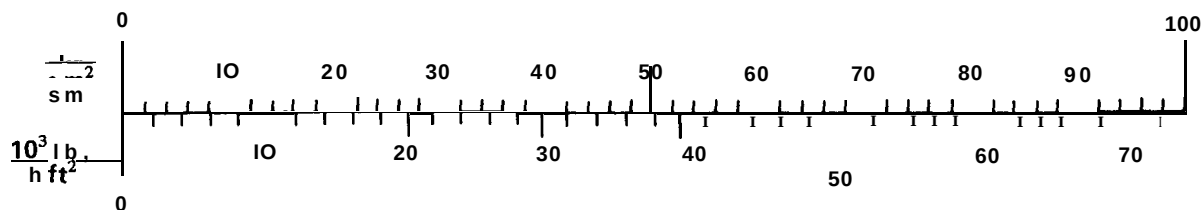
VELOCITY: $\frac{\text{m}}{\text{s}}$; $\frac{\text{ft}}{\text{s}}$



$$\frac{\text{m}}{\text{s}} \times 3.28 = \frac{\text{ft}}{\text{s}}$$

$$\frac{\text{ft}}{\text{s}} \times 0.305 = \frac{\text{m}}{\text{s}}$$

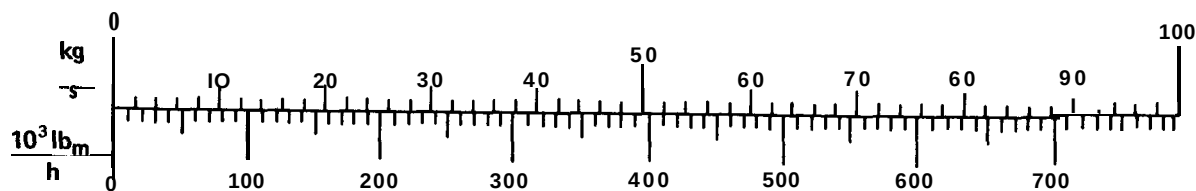
MASS VELOCITY: $\frac{\text{kg}}{\text{s m}^2}$; $\frac{10^3 \text{ lb}_m}{\text{h ft}^2}$



$$\frac{\text{kg}}{\text{s m}^2} \times 0.737 = \frac{10^3 \text{ lb}_m}{\text{h ft}^2}$$

$$\frac{10^3 \text{ lb}_m}{\text{h ft}^2} \times 1.356 = \frac{\text{kg}}{\text{s m}^2}$$

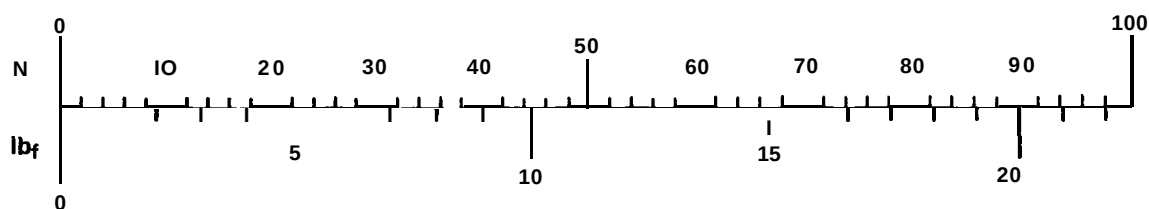
MASS FLOW RATE: $\frac{\text{kg}}{\text{s}}$; $\frac{10^3 \text{ lb}_m}{\text{h}}$



$$\frac{\text{kg}}{\text{s}} \times 7.937 = \frac{10^3 \text{ lb}_m}{\text{h}}$$

$$\frac{10^3 \text{ lb}_m}{\text{h}} \times 0.123 = \frac{\text{kg}}{\text{s}}$$

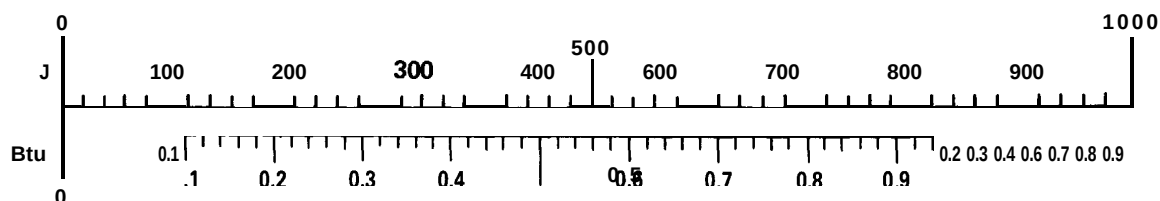
FORCE: newton, $\text{N} = \frac{\text{kg m}}{\text{s}^2}$; pound-force, lb_f



$$\text{N} \times 0.225 = \text{lb}_f$$

$$\text{lb}_f \times 4.448 = \text{N}$$

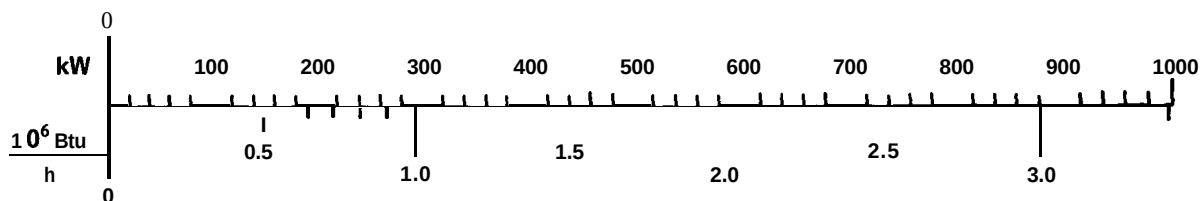
ENERGY (WORK): joule, $\text{J} = \text{N m}$; Btu



$$\text{J} \times 0.948(10^{-3}) = \text{Btu}$$

$$\text{Btu} \times 1055 = \text{J}$$

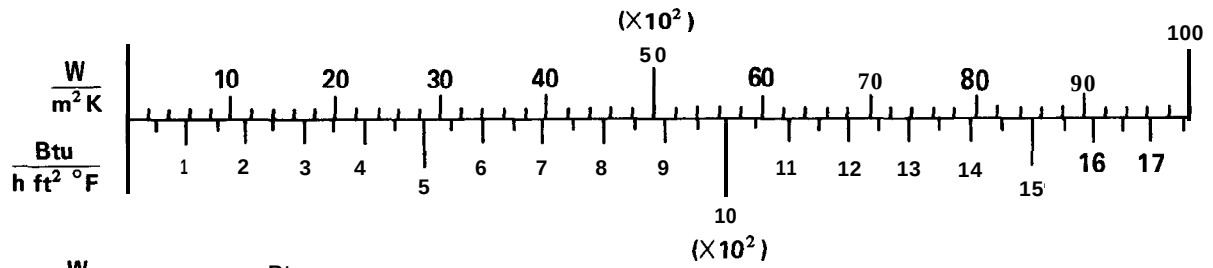
POWER OR ENERGY FLOW RATE: kilowatt, $\text{kW} = \frac{\text{kJ}}{\text{s}}$; $\frac{10^6 \text{ Btu}}{\text{h}}$



$$\text{kW} \times 3.412(10^{-3}) = \frac{10^6 \text{ Btu}}{\text{h}}$$

$$\frac{10^6 \text{ Btu}}{\text{h}} \times 293 = \text{kW}$$

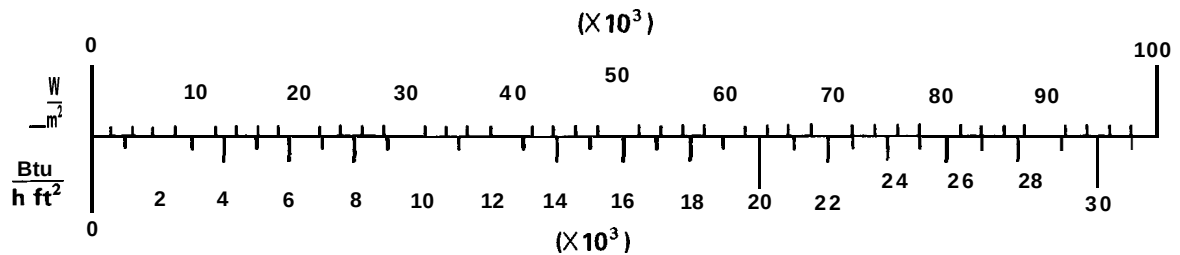
HEAT TRANSFER COEFFICIENT: $\frac{W}{m^2 K}$; $\frac{Btu}{h ft^2 ^\circ F}$



$$\frac{W}{m^2 K} \times 0.176 = \frac{Btu}{h ft^2 ^\circ F}$$

$$\frac{Btu}{h ft^2 ^\circ F} \times 5.68 = \frac{W}{m^2 K}$$

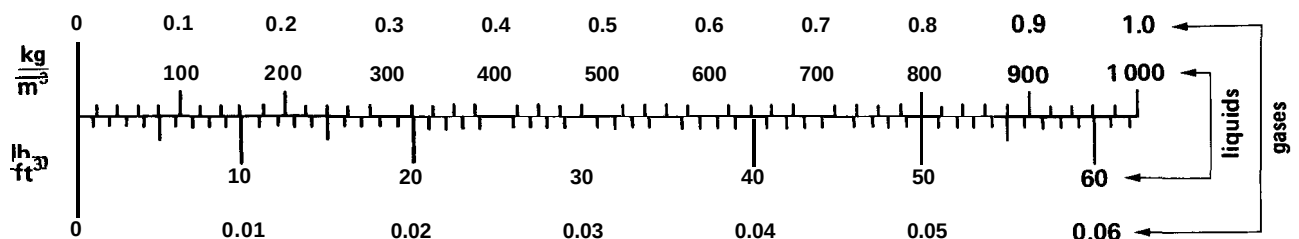
HEAT FLUX: $\frac{W}{m^2}$; $\frac{Btu}{h ft^2}$



$$\frac{W}{m^2} \times 0.316 = \frac{Btu}{h ft^2}$$

$$\frac{Btu}{h ft^2} \times 3.16 = \frac{W}{m^2}$$

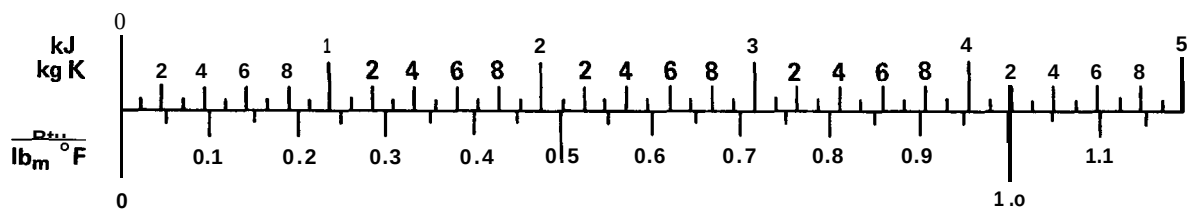
DENSITY: $\frac{kg}{m^3}$; $\frac{lb_m}{ft^3}$



$$\frac{kg}{m^3} \times 0.0624 = \frac{lb_m}{ft^3}$$

$$\frac{lb_m}{ft^3} \times 16.02 = \frac{kg}{m^3}$$

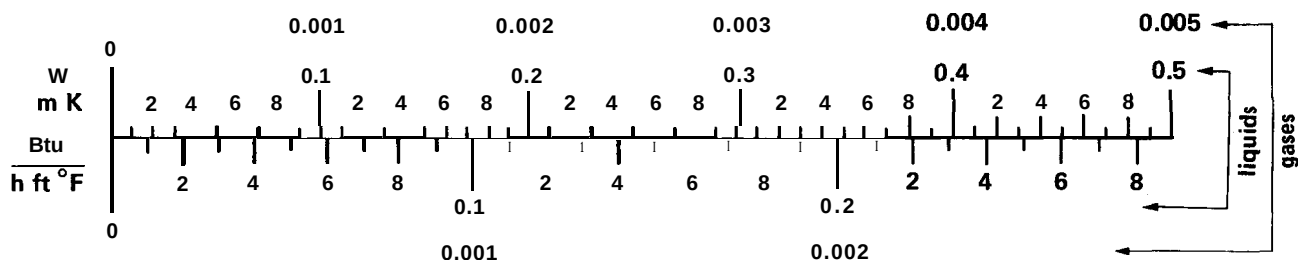
SPECIFIC HEAT CAPACITY: $\frac{\text{kJ}}{\text{kg K}}; \frac{\text{Btu}}{\text{lb}_m \text{ } ^\circ\text{F}}$



$$\frac{\text{kJ}}{\text{kg K}} \times 0.239 = \frac{\text{Btu}}{\text{lb}_m \text{ } ^\circ\text{F}}$$

$$\frac{\text{Btu}}{\text{lb}_m \text{ } ^\circ\text{F}} \times 4.187 = \frac{\text{kJ}}{\text{kg K}}$$

THERMAL CONDUCTIVITY: $\frac{\text{W}}{\text{m K}}; \frac{\text{Btu}}{\text{h ft } ^\circ\text{F}}$

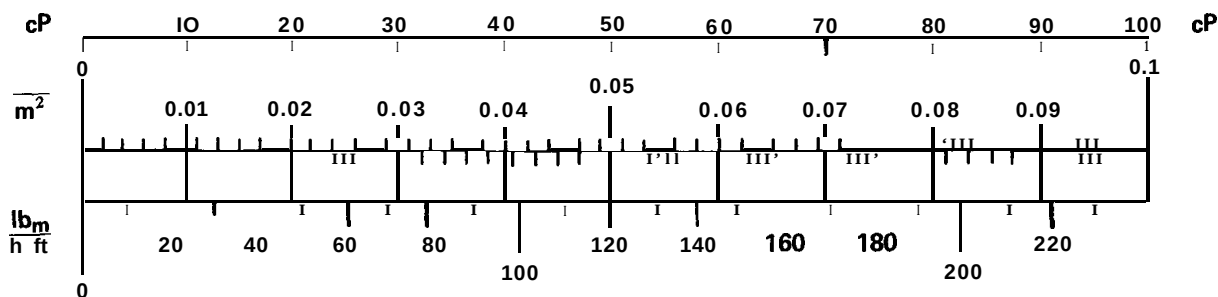


$$\frac{\text{W}}{\text{m K}} \times 0.578 = \frac{\text{Btu}}{\text{h ft } ^\circ\text{F}}$$

$$\frac{\text{Btu}}{\text{h ft } ^\circ\text{F}} \times 1.731 = \frac{\text{W}}{\text{m K}}$$

DYNAMIC (ABSOLUTE) VISCOSITY: $\frac{\text{N s}}{\text{m}^2}; \frac{\text{lb}_m}{\text{h ft}}$

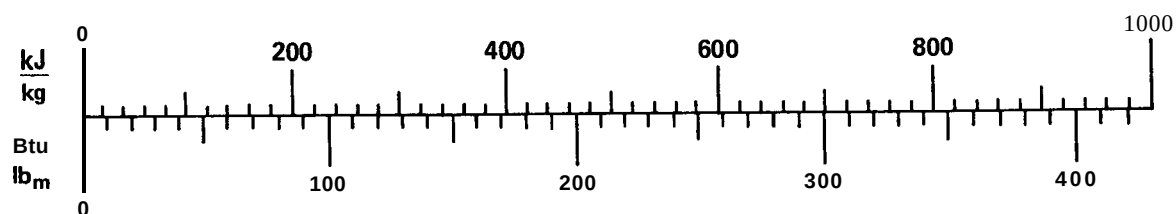
$$\text{centipoise cP} = 10^{-3} \frac{\text{N s}}{\text{m}^2} = \text{mPa s}$$



$$\text{cP} \times 2.42 = \frac{\text{lb}_m}{\text{h ft}}$$

$$\frac{\text{lb}_m}{\text{h ft}} \times 0.413 = \text{cP}$$

ENTHALPY: $\frac{\text{kJ}}{\text{kg}}$, $\frac{\text{Btu}}{\text{lb}_m}$

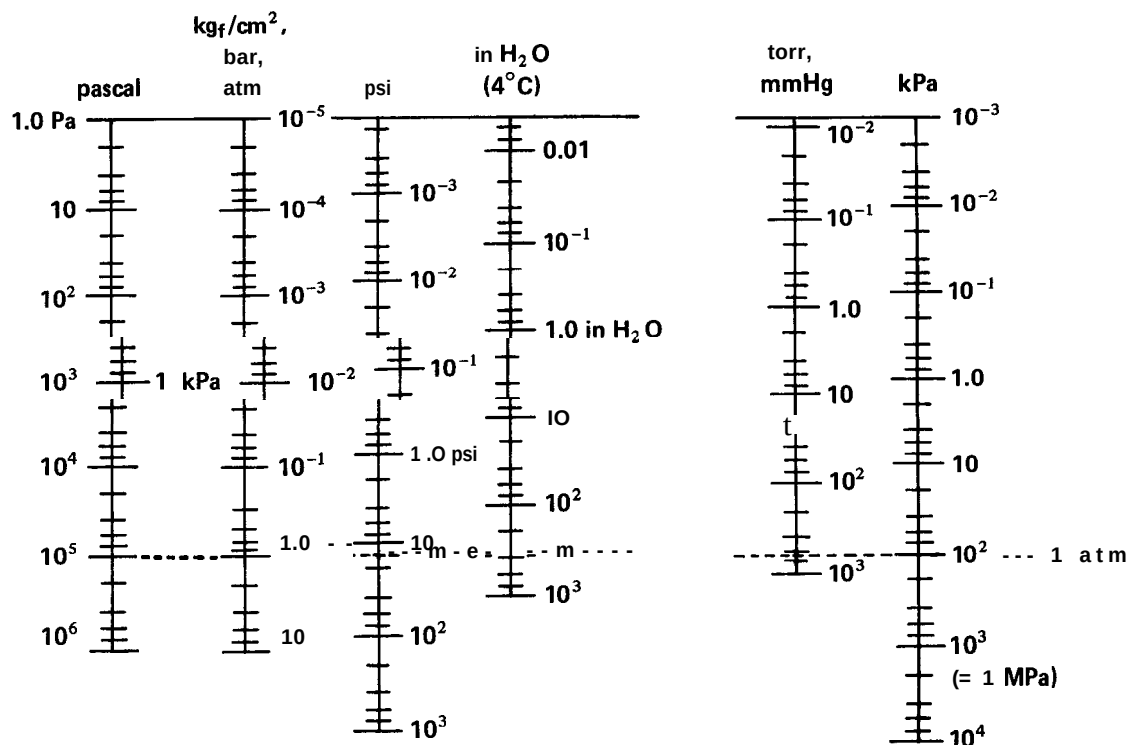


$$\frac{\text{kJ}}{\text{kg}} \times 0.430 = \frac{\text{Btu}}{\text{lb}_m}$$

$$\frac{\text{Btu}}{\text{lb}_m} \times 2.326 = \frac{\text{kJ}}{\text{kg}}$$

PRESSURE CONVERSION CHART

(top line = 1 Pa on all charts)

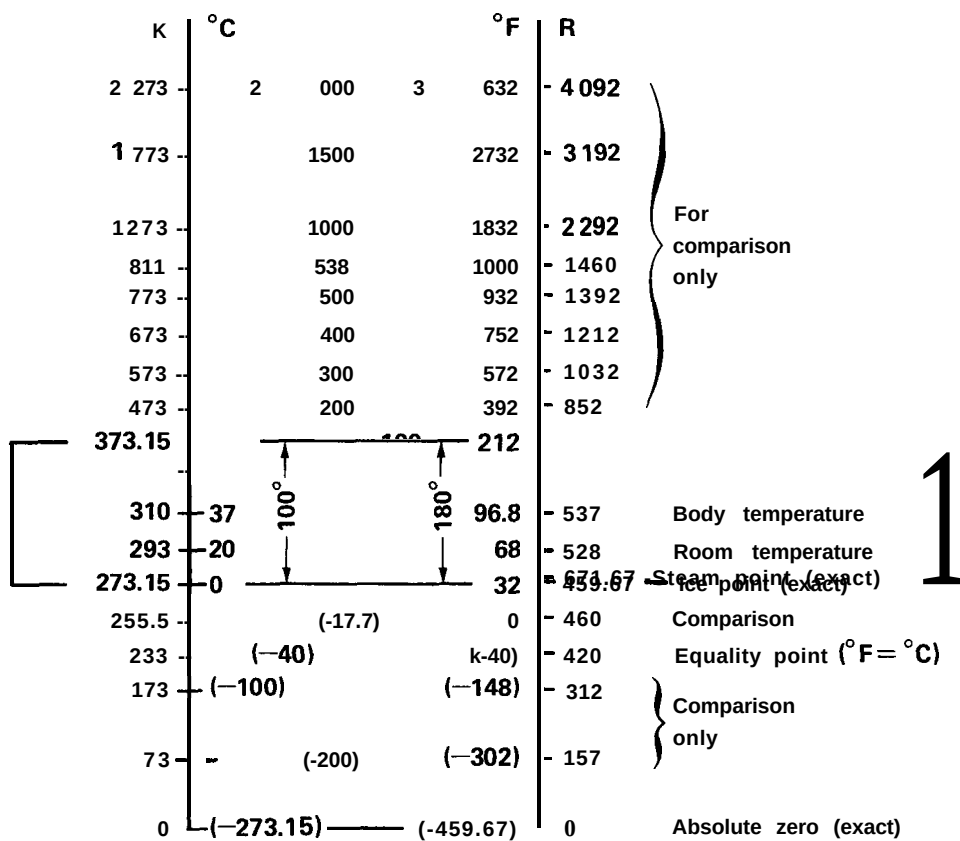


*NOTE: only bar is exact (1 bar = 10^5 Pa); however, atm and kgf/cm^2 are within 2% accuracy (see list below).

1 atm = 1.01325×10^5 Pa
 1 psi = 6.89476×10^3 Pa
 1 in H_2O = 2.49082×10^2 Pa
 1 kgf/cm^2 = 9.80665×10^4 Pa
 1 bar = 10^5 Pa
 1 mmHg = 1.33322×10^2 Pa

1 Pa = 9.86923×10^{-6} atm
 1 Pa = 1.45038×10^{-4} psi
 1 Pa = 4.01474×10^{-3} in H_2O
 1 Pa = 1.01972×10^{-5} kgf/cm^2
 1 Pa = 10^{-5} bar
 1 Pa = 7.50064×10^{-3} mmHg

TEMPERATURE COMPARISON
(NOT TO SCALE)



$$T(^{\circ}\text{F}) = (^{\circ}\text{C} + 40) \frac{9}{5} - 40$$

$$T(^{\circ}\text{C}) = (^{\circ}\text{F} + 40) \frac{5}{9} - 40$$

$$AT: ^{\circ}\text{C} = \frac{5}{9} (^{\circ}\text{F}) \quad ^{\circ}\text{F} = \frac{9}{5} (^{\circ}\text{C})$$

$$T(\text{R}) = T(^{\circ}\text{F}) + 460$$

$$T(\text{K}) = T(^{\circ}\text{C}) + 273.15$$

5.1

Properties of pure fluids

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5.1.0

Introduction

M. Schunck

■ The design of heat exchanging equipment is strongly influenced by the physical properties of the fluids to be heated or cooled, as far as they are important for determining heat transfer rates, pressure drops, and momentum. A great number of physical property data for various fluids are listed in Sec. 5.5, but it sometimes occurs that for a certain fluid no data are available or the range of given data is not sufficient. In order to cover these cases many methods for estimating properties of gases **and** liquids have been developed. Some of them are simple and easy to employ, but—due to the real nature of the phenomena, which is generally complicated—their results are not too reliable. More elaborate methods can give better results, but they are often restricted to

limited groups of compounds (mostly organic). Some of these methods can be evaluated economically only with the aid of a computer. Very good collections of estimating methods have been published, especially Reid et al. [1] or Hecht et al. [2].

In this chapter an attempt is made to give some of the simpler rules and methods **which** may be sufficient in many cases. At least, they may help to decide if more elaborate methods or the services of a data center are required where not only the available data but also the most modern estimating methods are computerized. This step is recommended in all cases where the exactness of the data is essential.

References to Section 5.1.0 appear at the end of Section 5.1.5.

5.1.1

Critical data

M. Schunck

A. Correspondence principle

Sometimes, the critical data of a fluid are of interest in themselves. This is especially the case where processes are carried out in the neighborhood of the critical state which employ liquefaction or vaporization or where the existence of two phases is required or prohibited.

On the other hand, knowledge of the critical data may often be essential since by using critical temperature, critical pressure, and critical volume, correspondences in the thermodynamic behavior of fluids can be found. This leads to the widely employed principle of correspondence which uses reduced state parameters, i.e., dimensionless parameters of state obtained by dividing the real parameters by the corresponding critical parameters:

$$T_r = \frac{T}{T_c} \quad p_r = \frac{p}{p_c} \quad \tilde{V}_r = \frac{\tilde{V}}{\tilde{V}_c}$$

Ideally, it might be possible to link these reduced parameters together by a universal equation of state, valid for all fluids.

Numerous investigations, however, have shown that this is only possible for relatively small groups of similar fluids. Common equations of state even for normal fluids can be established only by using additional parameters. These, in many cases, are correlated again to the critical data. Riedel [3a] defines the critical parameter α_c :

$$\alpha_c = \left(\frac{d \ln p_{rs}}{d \ln T_{rs}} \right)_c \quad (1)^\dagger$$

where p_{rs} and T_{rs} represent pairs of reduced pressure and reduced temperature values according to the saturation curve. The parameter is used in correlations with its value at the critical point, α_c , only.

An equivalent of the critical parameter α_c is the acentric factor ω defined by Pitzer [4]:

$$\omega = -(\log p_{rs(0.7)} + 1) \quad (2)$$

where $p_{rs(0.7)}$ is the reduced pressure on the saturation curve at a reduced temperature of $T_{rs} = 0.7$. Correspondence relations using α_c or ω are sometimes recommended in the following paragraphs.

B. Critical temperature

Guldberg's rule can give a rough estimate of critical temperature:

$$T_c \approx 1.5 T_b \quad \text{or} \quad \frac{T_b}{T_c} \approx \frac{2}{3} \quad (3)$$

where T_b is the boiling temperature at normal pressure.

[†]Within a three-digit section the equation, figure, and table numbers do not have the three-digit identifier; for cross-references between sections, the appropriate three-digit number will be given.

Table 1 Atomic and structural constants used in Lydersen's method for calculating critical data of organic compounds^{a, b}

Group	ΔT	Δp	ΔV
Basic value		—	0.040
—CH ₃ and —CH ₂ —	0.020	0.225	0.055
—CH ₃ — member of ring	0.013	0.183	0.044 5
—CH	0.012	0.209	0.051
—CH member of ring	0.012	0.191	0.046
=CH and =CH ₂	0.018	0.197	0.045
=CH member of ring	0.011	0.153	0.037
C	0.000	0.209	0.041
C member of ring	(-0.007)	(0.153)	(0.031)
=C and =C=	0.000	0.197	0.036
Same, member of ring	0.011	0.153	0.036
≡C— and ≡CH	0.005	0.152	(0.036)
- F	0.018	0.222	0.018
- Cl	0.017	0.318	0.049
- Br	0.010	0.496	(0.070)
- I	(0.012)	(0.824)	(0.095)
- o -	0.021	0.159	0.020
-O- member of ring	(0.014)	(0.119)	(0.008)
-OH alcohols	0.082	0.060	0.018
-OH phenols	(0.035)	(-0.020)	(0.003)
c o	0.040	0.288	0.060
CO member of ring	(0.033)	(0.199)	(0.050)
-CHO	0.048	0.328	0.073
—COO—	0.047	0.467	0.080
—COOH	0.085	0.397	0.080
—NH ₂	0.031	0.097	0.028
NH	0.031	0.137	(0.037)
NH member of ring	(0.024)	(0.089)	(0.027)
N	0.014	0.169	0.042
N- member of ring	(0.007)	(0.129)	(0.032)
-C.N	(0.060)	(0.357)	(0.080)
—SH and -S-	0.015	0.268	0.055
-S- member of ring	(0.008)	(0.238)	(0.045)
= s	0.003	(0.238)	0.047
=O	(0.020)	(0.119)	(0.011)
-NO,	(0.055)	(0.417)	(0.078)

^aAccording to Lydersen [5].

^bUncertain values in parentheses.

(Real values of T_b/T_c vary from 0.55 to 0.72 with 0.364 for mercury.)

More reliable values for organic compounds are obtained by Lydersen's incremental method [5]:

$$\frac{T_b}{T_c} = 0.567 + \Sigma \Delta T + (\Sigma \Delta T)^2 \quad (4)$$

where $\Sigma \Delta T$ is determined from atomic and structural constants as listed in Table 1. (The deviation is $\pm 2\%$ on average with a maximum of $\pm 7\%$.)

C. Critical pressure

No simple rule exists for calculating critical pressure other than extrapolating the saturation curve (see Sec.

5.1.3B), if the critical temperature is known. Lydersen's incremental method [5] gives

$$p_c = \frac{M}{(\Sigma \Delta p + 0.33)^2} \text{ bar} \quad (5)$$

where 1 bar = 10^5 N/m^2 , and again $\Sigma \Delta p$ is composed of atomic and structural constants as listed in Table 1. (The deviation is $\pm 2\%$ on average with a maximum of $\pm 20\%$.)

D. Critical volume

According to the rule of Cailletet and Mathias [6] [see Sec. 5.1.2A and Fig. 5.1.2(1)], the mean value of liquid and vapor density in the saturated state plotted against

Table 2 Numerical values of the functions $\phi(T_r)$ and $\psi(T_r)$ for the calculation of the critical parameter α_c according to Riedel [3a]

T_r	ϕ	ψ	T_r	ϕ	ψ
0.35	6.003	1.321	0.70	1.242	0.203
0.36	5.719	1.248	0.71	1.182	0.192
0.37	5.452	1.179	0.72	1.125	0.181
0.38	5.200	1.115	0.73	1.069	0.171
0.39	4.963	1.055	0.74	1.015	0.161
			0.75	0.962	0.152
0.40	4.739	0.999	0.76	0.911	0.143
0.41	4.527	0.946	0.77	0.862	0.134
0.42	4.326	0.896	0.78	0.814	0.126
0.43	4.135	0.850	0.79	0.767	0.118
0.44	3.955	0.805			
0.45	3.783	0.764	0.80	0.722	0.110
0.46	3.619	0.724	0.81	0.677	0.103
0.47	3.463	0.687	0.82	0.635	0.096
0.48	3.315	0.652	0.83	0.593	0.089
0.49	3.174	0.619	0.84	0.552	0.082
			0.85	0.512	0.076
0.50	3.039	0.588	0.86	0.473	0.070
0.51	2.909	0.558	0.87	0.435	0.064
0.52	2.786	0.530	0.88	0.398	0.058
0.53	2.668	0.503	0.89	0.361	0.053
0.54	2.555	0.477			
0.55	2.447	0.453	0.90	0.325	0.047
0.56	2.343	0.430	0.91	0.290	0.042
0.57	2.243	0.409	0.92	0.256	0.037
0.58	2.147	0.388	0.93	0.222	0.032
0.59	2.055	0.368	0.94	0.189	0.027
			0.95	0.157	0.023
0.60	1.967	0.349	0.96	0.124	0.018
0.61	1.882	0.331	0.97	0.093	0.013
0.62	1.800	0.314	0.98	0.061	0.009
0.63	1.721	0.298	0.99	0.031	0.004
0.64	1.645	0.283			
0.65	1.572	0.268	1.00	0.000	0.000
0.66	1.501	0.254			
0.67	1.433	0.240			
0.68	1.367	0.227			
0.69	1.303	0.215			

temperature is nearly a straight line that includes the critical point. Thus, if some sets of saturated liquid and vapor densities are known together with the critical temperature, the critical specific volume can be estimated.

For organic fluids, Lydersen's incremental method [5] gives

$$\tilde{V}_c = \Sigma \Delta V + 0.040 \quad \text{m}^3/\text{kmol or dm}^3/\text{mol} \quad (6)$$

where $\Sigma \Delta V$ is composed of atomic and structural constants as listed in Table 1. (The deviation is $\pm 3\%$ on average with a maximum of $\pm 10\%$.)

E. Critical parameter a , and acentric factor ω

If α_c cannot be evaluated according to its original definition (see Sec. A), Riedel [3a] gives the equation

$$\alpha_c = \frac{\log(1/p_{rs}) - \phi(T_{rs})}{\psi(T_{rs})} + \gamma \quad (7)$$

where p_{rs} and T_{rs} are the reduced vapor pressure and the reduced equilibrium temperature of one known pair of values of the saturation curve, and the functions

$$\phi(T_{rs}) = 0.1183 \left(\frac{36}{T_{rs}} - 35 - T_{rs}^6 \right) + 4.44 \log T_{rs} \quad (8)$$

and

$$\psi(T_{rs}) = 0.0364 \left(\frac{36}{T_{rs}} - 35 - T_{rs}^6 \right) + 2.52 \log T_{rs} \quad (9)$$

Values of both functions are tabulated in Table 2.

The evaluation of the acentric factor ω in Flitzer's definition [4] (see Sec. A) requires knowledge of the vapor equilibrium pressure at a reduced temperature of $T_{rs} = 0.7$. For cases where this value is not available, Riedel [3f] links ω to α_c by the equation

$$\omega = \frac{\alpha_c - 5.811}{4.919} \quad (10)$$

Edmister [7] gives the equation

$$\omega = 0.429 \frac{T_b/T_c}{1 - T_b/T_c} (\log p_c - 0.9915) \quad (11)$$

where T_b/T_c as well as p_c can be estimated, if necessary, by the methods described in Secs. B and C. The critical pressure p_c has to be given in bars.

Nomenclature for Section 5.1.2 appears at the beginning of Part 5. References appear at the end of Section 5.1.5.

5.1.2

Specific volume, p - V - T correlations

M. Schunck

A. Specific volume of the liquid phase

According to the empirical rule of Cailletet and Mathias [6] the specific volumes V_{ls} of the saturated liquid and $\tilde{V}_{vs}$ of the saturated vapor at the same temperature follow the relationship

$$\frac{\tilde{M}}{2} \left(\frac{1}{\tilde{V}_{ls}} + \frac{1}{\tilde{V}_{vs}} \right) = 0.5(\rho_{ls} + \rho_{vs}) = a + bT + cT^2 + \dots \quad (1)$$

where the factors c , d , etc. are so small that for estimating purposes they may be neglected even in the neighborhood of the critical state. Thus, the rule states that in a plot of density versus temperature the mean values of saturated vapor and saturated liquid densities are represented by a straight line with a slope of b (see Fig. 1). If the specific volume of a liquid at low

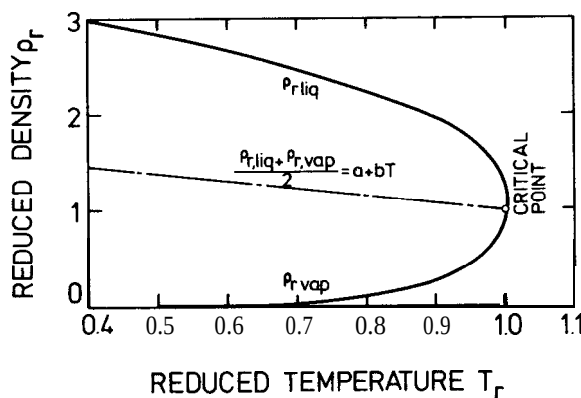


Figure 1 Rule of Cailletet and Mathias: Example, propane.

temperature is known together with its critical volume and the specific volume of the saturated vapor, then this rule gives the specific volume of the saturated liquid throughout the whole temperature range.

According to Watson [8], the specific volume of a liquid can be related to the reduced pressure p_r and the reduced temperature T_r by the *expansion factor* ω^* using the equation

$$V\omega^* = c$$

where ω^* is a function of p_r and T_r shown in Fig. 2 and C is a constant that can be determined if a reliable value of the specific volume of the liquid is known together with the critical pressure and temperature. This method also applies to temperatures below or pressures above the saturated state.

For normal fluids in the saturated state Riedel [3b] gives the equation

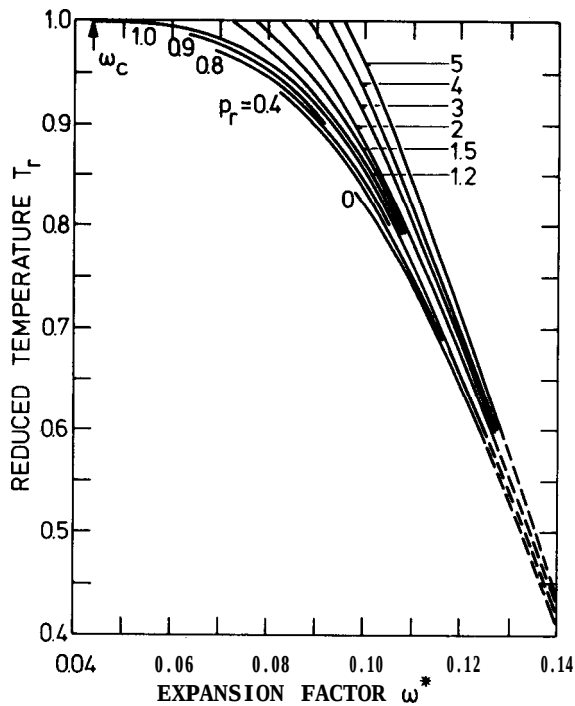
$$\tilde{V}_{lsr} = (1 + 0.85(1 - T_r) + [1.93 + 0.2(\alpha_c - 7)(1 - T_r)^3]^{-1})^{-1} \quad (2)$$

As T_r approaches 0, this equation approaches

$$\frac{V_0}{\tilde{V}_c} = \frac{1}{3.78 + 0.2(\alpha_c - 7)} \quad (3)$$

where $\tilde{V}_0$ is the (merely fictitious) specific volume at $T_r = 0$. Timmermans [9] stated that for most liquids $\tilde{V}_0/\tilde{V}_c = Z_c$, where Z_c is the critical compressibility factor

$$Z_c = \frac{p_c \tilde{V}_c}{\tilde{R} T_c} \quad (4)$$

Figure 2 Expansion factor ω^* according to Watson [8].

with values commonly in the range of $Z_c = 0.265 \pm 0.015$. Riedel [3b] has tabulated the numerical values of $\tilde{V}_{lsr}/Z_c$ as a function of T_r . (See Table 1 which is reciprocal to Riedel's original table.) It should be noted that the influence of a , is very small below $T_r = 0.8$.

Rackett [10] showed that the simpler equation

$$\tilde{V}_{lsr} = Z_c^{(1-T_r)^{0.285}} \quad (5)$$

is also a very good approximation. The critical compressibility factor Z_c in this equation can be estimated according to Riedel (see above) or according to Yamada and Gunn [11] using Pitzer's acentric factor ω :

$$Z_c = 0.291 - 0.0878\omega \quad (6)$$

B. Coefficient of volumetric thermal expansion of liquids

In the tables of Sec. 5.5, the densities of numerous liquids are given for various temperatures. From these or other known values, the coefficient of volumetric thermal expansion $\beta = [\partial \tilde{V}/(\tilde{V} \partial T)]_p$ can be calculated or graphically evaluated. If no values of density or specific volume are available, β can be estimated using the expansion factor ω^* (see Fig. 2).

From $\tilde{V} = C(\omega^*)^{-1}$ follows

$$\left(\frac{\partial \tilde{V}}{\partial \omega^*} \right)_p = -\frac{1}{\omega^*} \quad (7)$$

and

$$\begin{aligned} \beta &= \left(\frac{\partial \tilde{V}}{\partial T} \right)_p = \left(\frac{\partial \tilde{V}}{\partial \omega^*} \frac{\partial \omega^*}{\partial T} \right)_p \\ &= -\frac{1}{\omega^*} \left(\frac{\partial \omega^*}{\partial T} \right)_p \end{aligned} \quad (8)$$

which can be graphically evaluated from Fig. 2.

Differentiation of the Rackett equation [9] (see Sec. A) gives

$$\beta = -\frac{0.285 \ln Z_c}{T_c(1-T_r)^{0.715}} \quad K^{-1} \quad (9)$$

or with $Z_c \approx 0.265 \pm 0.015$

$$\beta = +\frac{0.380 \pm 0.015}{T_c(1-T_r)^{0.715}} \quad K^{-1} \quad (10)$$

Here, however, the fact is neglected that Rackett's equation is valid for the saturated liquid, i.e., for a pressure varying with temperature. This limits the validity of the above relationship to a temperature range not much above the normal boiling point.

C. Specific volume of gases

At low reduced pressures and high reduced temperatures, the ideal gas law applies quite correctly:

$$p\tilde{V} = \tilde{R}T \quad (11)$$

(If p is in N/m^2 , $\tilde{V}$ in $m^3/kmol$, and T in K , then $\tilde{R}$, the universal gas constant, has a value of 8 314.3 J/kmol.) At higher pressures or near the condensing temperature, the law of ideal gases no longer applies. However, the behavior of real gases and vapors can be related to that of ideal gases by introducing a factor of compressibility,

$$Z = \frac{p\tilde{V}}{\tilde{R}T} \quad (12)$$

The dimensionless factor Z is dependent upon temperature, pressure, and thermodynamical properties of the gas or vapor. It can be given as a function of reduced state parameters, thus permitting a fairly good prediction of the $p-V-T$ behavior of any gas.

In Fig. 3, Z is plotted in accordance with Nelson and Obert [12] as well as Riedel [3f] for $\alpha_c = 6$ in the range $0.8 < T_r < 15$. The deviations for different values of α_c are fairly small. Riedel [3f] gives more extensive tabulations of $\partial Z/\partial \alpha_c$.

The dotted lines in Fig. 3 apply to an ideal reduced specific volume, $\tilde{V}_{rid}$, which can be used without knowledge of the critical volume $\tilde{V}_c$ in the calculation of corresponding pressure-temperature values for a given specific volume:

$$\tilde{V}_{rid} = \tilde{V} \frac{p_c}{\tilde{R}T_c} = \frac{Z\tilde{R}Tp_c}{p\tilde{R}T_c} = Z \frac{T_r}{p_r} \quad (13)$$

Table 1 Numerical values^a of $\tilde{V}_{lsr}/Z_c$

T_r	0.3	0.35	0.4	0.45	0.5	0.55	0.6	0.65	0.7
$\tilde{V}_{lsr}/Z_c$	1.142	1.172	1.205	1.239	1.279	1.321	1.368	1.422	1.484
T_r	0.75	0.8	0.85	0.9	0.95	0.97	0.98	0.99	1.0
$\alpha_c = 6$	1.557	1.642	1.751	1.898	2.132	2.288	2.410	2.591	3.584
7	1.558	1.645	1.755	1.908	2.155	2.326	2.451	2.653	3.774
8	1.559	1.647	1.759	1.919	2.179	2.358	2.494	2.710	3.984

Abbreviated from Riede[3b].

D. Coefficient of volumetric thermal expansion of gases

For ideal gases, the volumetric thermal expansion is described by

$$\beta = \left(\frac{\partial \tilde{V}}{\tilde{V} \partial T} \right)_p = \frac{1}{T} \quad \text{K}^{-1} \quad (14)$$

In any case where $Z \neq 1$ or $Z \neq \text{const}$ (e.g., at higher pressures), this equation is changed to

$$\beta = \left(\frac{\partial Z}{Z \partial T} \right)_p \quad (15)$$

where $\partial Z/\partial T$ at constant (reduced) pressure can be graphically evaluated from Fig. 3.

Of course, it is also possible to calculate two values of $\tilde{V}$ at the same pressure but different temperatures and take

$$\beta = \left(\frac{\Delta \tilde{V}}{\tilde{V} \Delta T} \right)_p \quad (16)$$

but this procedure also requires careful evaluation of $(\Delta Z/\Delta T)_p$.

E. Equations of state

Analytical formulations of the relationships among p , $\tilde{V}$, and T are called equations of state. Many of them have been developed, the first one by van der Waals [13] in 1873:

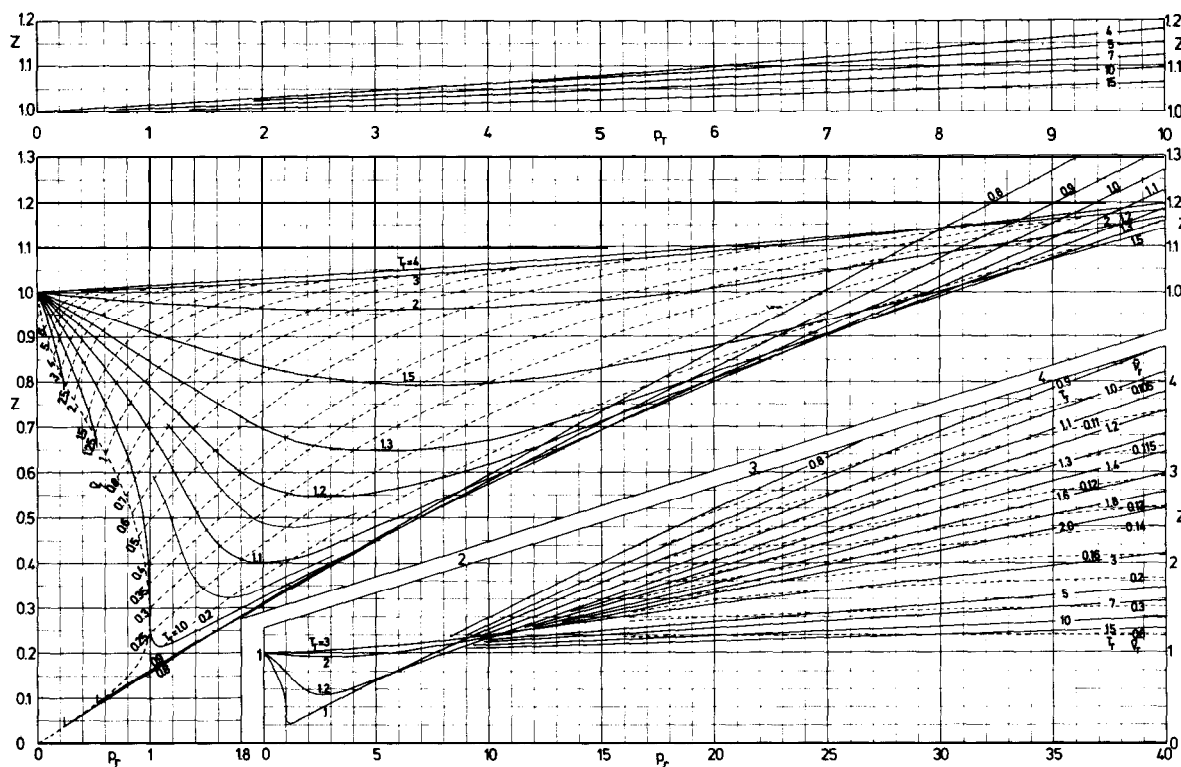


Figure 3 Compressibility factor $Z = p\tilde{V}/RT$ as a function of p_r and T_r for $\alpha_c = 6$ [3f, 12].

$$\left(p + \frac{a}{\tilde{V}^2}\right)(\tilde{V} - b) = \tilde{R}T \quad (17)$$

where a and b are specific constants approaching 0 for ideal gas conditions. This is one condition that should be fulfilled by any equation of state, but all of them should also satisfy the conditions at the critical point:

$$\left(\frac{dp}{d\tilde{V}}\right)_{T_c} = 0 \quad (18)$$

$$\left(\frac{d^2p}{d\tilde{V}^2}\right)_{T_c} = 0 \quad (19)$$

With this requirement, the values of a and b in the van der Waals equation become

$$a = \left(\frac{3}{4}\right)^3 \frac{(\tilde{R}T_c)^2}{p_c} \quad b = \frac{1}{2} \left(\frac{1}{2}\right)^3 \frac{\tilde{R}T_c}{p_c} \quad (20)$$

The best compromise between simplicity and accuracy seems to be provided by the Redlich-Kwong equation [14], which is also a two-constant equation:

$$\left[p + \frac{a}{T^{0.5}\tilde{V}(\tilde{V} + b)}\right](\tilde{V} - b) = \tilde{R}T \quad (21)$$

or

$$p = \frac{RT}{\tilde{V} - b} - \frac{aT^{-0.5}}{\tilde{V}(\tilde{V} + b)}$$

with the constants a and b derived by similar considerations as for the van der Waals equation:

$$a = 0.4275 \frac{\tilde{R}^2 T_c^{2.5}}{p_c} \quad (22)$$

$$b = 0.08664 \frac{\tilde{R}T_c}{p_c} \quad (23)$$

Soave [15] improved the accuracy of the Redlich-Kwong equation, replacing the term $aT^{-0.5}$ by a function of the reduced temperature and Pitzer's acentric factor. The whole equation then reads

$$p = \frac{\tilde{R}T}{\tilde{V} - b}$$

$$-a_c [1 + (0.480 + 1.574 \omega - 0.176 \omega^2) \cdot (1 - T_r^{0.5})]^2 / \tilde{V}(\tilde{V} + b) \quad (24)$$

where

$$a_c = (aT^{-0.5})_c = 0.4275 \frac{\tilde{R}^2 T_c^2}{p_c} \quad (25)$$

and

$$b = 0.08664 \frac{\tilde{R}T_c}{p_c} \quad (26)$$

as above.

A further modification of the Redlich-Kwong equation, suggested by Peng and Robinson [16] is reported to be even more accurate for hydrocarbons and hydrates and for liquid densities than the Redlich-Kwong-Soave version:

$$p = \frac{\tilde{R}T}{\tilde{V} - b_1} - a_{c1} [1 + (0.375 + 1.542 \omega - 0.207 \omega^2) \cdot (1 - T_r^{0.5})]^2 / (\tilde{V} + b_1)^2 - 2b_1^2 \quad (27)$$

with a_{c1} and b_1 slightly different from a , and b as a consequence of the different structure of the equation:

$$a_{c1} = 0.4572 \frac{\tilde{R}^2 T_c^2}{p_c} \quad (28)$$

$$b_1 = 0.0778 \frac{\tilde{R}T_c}{p_c} \quad (29)$$

For many compounds the virial coefficients for the virial equation of state,

$$z = \frac{pV}{\tilde{R}T} = 1 + B(T) + C(T)\tilde{\rho}^2 + D(T)\tilde{\rho}^3 + \dots \quad (30)$$

are given in the literature. B , the second virial coefficient, C , the third virial coefficient, etc., are functions of temperature only for pure fluids.

Other, more elaborate equations of state, e.g., Benedict-Webb-Rubin, or Lee-Kesler, are beyond the scope of this section. See Ref. [1].

Nomenclature for Section 5.1.2 appears at the beginning of Part 5. References appear at the end of Section 5.1.5.

5.1.3

Thermodynamic properties

M. Schunck

A. Normal boiling point

The normal **boiling** point of a pure fluid (at normal pressure, 760 mm Hg = 1.013 3 bar) is rarely unknown since the experimental determination is very easy. The estimating methods presented below will therefore be more or less a last refuge.

For a large number of organic compounds the normal boiling point can be determined according to Ogata and Tsuchida [17] from structural constants listed in Table 1. With the constants p , y , and q taken from this table, the normal boiling temperature is

$$T_b = py + q \quad K \quad (1)$$

All other existing rules for estimating the normal boiling temperature of a fluid solely from the knowledge of its chemical composition are reported to be less accurate than simple considerations of analogy with similar compounds whose boiling points are known.

If some points of the vapor pressure-temperature curve are available, the normal boiling point can be found by extrapolating or interpolating. For this purpose it is either possible to draw a vapor pressure curve in a diagram like a Cox chart (see Sec. B) where it is nearly a straight line, or to use the Antoine equation. However, it has to be kept in mind that many liquid compounds will decompose at temperatures well below their normal boiling point.

B. Vapor pressure-temperature curves

A plot of $\log p$ versus T^{-1} for any compound gives a fairly straight curve that can be extrapolated or inter-

polated easily. Even if only two points of the whole function are known, e.g., the boiling point and the critical point, a line through these two points in the $\log p$ versus T^{-1} diagram is a good estimation for the relationship between saturation pressure and saturation temperature. It can be improved if it is drawn similar to a known curve or if more than two pairs of parameters are available for its determination.

A further improvement was first suggested by Cox [18]: A plot of $\log p$ over a function of T is graphically generated by drawing a straight line with a positive or negative slope into a coordinate system. The ordinate is then marked up in $\log p$ and the abscissa in T according to the known equilibrium values of a reference fluid, e.g., water. In such a diagram, since named Cox chart, the vapor pressure-temperature curves of other fluids are found to plot as almost straight lines too.

Hoffmann and Florin [19] gave an analytical function for the abscissa of a Cox chart, which is linear in τ^{-1} instead of T^{-1} :

$$\tau^{-1} = T^{-1} - (7.915 \cdot 10^{-6} - 2.672 \cdot 10^{-6} \log T) \times 10^{-3} - 0.862 \cdot 10^{-6} T \quad (2)$$

A tabulation of corresponding values of T^{-1} and τ^{-1} is given in Table 2. This tabulation is especially useful when values of a Cox chart are to be interpolated. Two Cox charts, for several fluids, prepared according to Hoffmann and Florin are presented in Figs. 1 and 2. Cox charts like these show an interesting and sometimes useful peculiarity: the vapor pressure-temperature curves of homologous series of compounds often (nearly) meet in one point. In many cases this infinite

Table 1 Structural constants p , q , and y for the estimation of normal boiling points of organic liquids

Rx	p	q	(Ex) ^b
RH	1.615	63.8	Me, ^c <i>t</i> -Bu
RCl	1.348	197.7	
RBr	1.260	213.6	
RI	1.198	253.4	
ROH	0.896	277.6	Me, <i>t</i> -Bu
MeOR	1.217	191.2	Me
EtOR	1.137	221.8	
ROR	2.158	143.2	Me, Hep
PhOR	0.894	377.4	
RONO,	1.016	280.5	
RSH	1.191	221.0	
RSMe	1.146	249.2	Me
RSEt	1.080	280.0	
RSR	1.937	214.4	Me, Hep
RNH ₂	1.194	201.4	
RNHMe	1.180	215.2	
RNH ₂ Et	1.081	247.9	
RNHPr	0.991	282.8	
RNMe	1.193	218.7	Me
RNO,	0.923	308.8	
HCOR	1.140	233.8	
MeCOR	1.022	270.6	
EtCOR	0.918	302.2	
RCN	0.960	292.2	
RCOCl	1.040	267.9	
HCOOR	1.073	244.6	
MeCOOR	1.000	273.2	(Standard series)
EtCOOR	0.963	297.5	
PhCOOR	0.766	425.9	
RCOOH	0.903	342.4	
RCOOMe	1.000	273.2	(Standard series)
RCOOEt	0.963	297.5	
RCOOPr	0.911	323.4	
RCOOPh	0.766	425.9	
(RCO) ₂ O	1.286	337.7	Hep
ClCH ₂ COOR	0.721	359.6	
Cl, CHCOOR	0.745	372.3	
BrCH ₂ COOR	0.745	374.4	
NCCH ₂ COOR	0.565	433.5	
CH, =CHCOOR	0.918	302.2	

R	Y	R	Y
Me	55.5	<i>t</i> -Am	122.0
Et	77.1	Neopent	125.0
<i>n</i> -Pr	102.0	<i>n</i> -Hex	171.0
iso-Pr	92.0	iso-Hex	168.0
<i>n</i> -Bu	124.0	<i>n</i> -Hep	191.5
sec-Bu	113.0	<i>n</i> -Oct	210.0
iso-Bu	116.5	Vinyl	71.0
<i>t</i> -Bu	96.0	Allyl	104.0
<i>n</i> -Am	149.0	2-Butenyl	127.0
iso-Am	140.5	Phenyl	197.0

^aAccording to Ogata and Tsuchida [17].^b(Ex) stands for configurations for which deviations of more than ±5% are to be expected.^cMe = methyl; Ph = phenyl, etc.

point is close to $\tau^{-1} = 0$ or $T = 1\,400\text{ K}$, and $p = 2\,250\text{ bars}$ or $\log p = 3.352$.

Antoine [20] proposed a simple equation for the vapor pressure-temperature equilibrium which also results in a distortion of the T^{-1} scale in a $\log p$ versus $f(T)$ correlation:

$$\log p = A - \frac{B}{T - C} \quad (3)$$

The constants A , B , and C for Antoine's equation are often given in the literature (see also Sec. 5.5). Antoine suggested that $C = 13\text{ K}$, but better results are claimed for a rule given by Thomson [21]:

$$C = -0.3 + 0.034 T_b \quad \text{K} \quad (4)$$

for fluids with $T_b < 125\text{ K}$ and for monatomic elements, while

$$C = -18 + 0.19 T_b \quad \text{K} \quad (5)$$

for all other fluids. Once a value for C is accepted, it is easy to calculate A and B from two known pairs of vapor pressure-temperature values, p_1, T_1 and p_2, T_2 :

$$B = \frac{\log p_2 - \log p_1}{(T_1 - C)^{-1} - (T_2 - C)^{-1}} \quad (6)$$

$$A = \log p_1 + \frac{B}{T_1 - C} = \log p_2 + \frac{B}{T_2 - C} \quad (7)$$

The Antoine equation is not dimensionless. If tabulated values of A , B , and C are to be used, one has to make sure if $\ln p$ or $\log p$ must be taken, and in which of the possible units p and even T (K or R) will be given.

C. Heat of vaporization

According to Trouton's rule [22], the increase of the molar entropy during vaporization at the normal boiling point is very similar for many fluids, being close to

$$\frac{\Delta \tilde{H}_v}{T_b} = 88 \text{ kJ/kmol K} \quad (8)$$

where $\Delta \tilde{H}_v$ is the molar heat of vaporization in J/mol or kJ/kmol.

Trouton's rule is a good approach for nonassociating fluids with normal boiling temperatures over 170 K. For other fluids, the deviations are sometimes considerable; instead of 88 kJ/kmol, the real values are, for instance, hydrogen, 46 kJ/kmol K; nitrogen, 71 kJ/kmol K; and water, 108 kJ/kmol K.

Better results are achieved by employing a "Trouton parameter" which is a function of the reduced pressure and the reduced temperature at the boiling point, p_{rb} and T_{rb} . Thus Trouton's rule changes to

Table 2 Numerical values of T^{-1} and τ^{-1} as functions of temperature for the distortion of the T^{-1} scale^a

θ °C	T K	$1/T$	$1/\tau$	θ °C	T K	$1/T$	$1/\tau$
-270	3.15	0.317 460	0.310 874	+ 60	333.15	0.003 002	0.001 541
-265	8.15	0.122 699	0.117 213	+ 70	343.15	0.002 914	0.001 479
-260	13.15	0.076 046	0.071 110	+ 80	353.15	0.002 832	0.001 422
-255	18.15	0.055 096	0.050 530	+ 90	363.15	0.002 754	0.001 368
-250	23.15	0.043 197	0.038 908	+100	373.15	0.002 680	0.001 317
-245	28.15	0.035 524	0.031 459	+110	383.15	0.002 610	0.001 269
-240	33.15	0.030 166	0.026 286	+120	393.15	0.002 544	0.001 224
-235	38.15	0.026 212	0.022 491	+130	403.15	0.002 481	0.001 181
-230	43.15	0.023 175	0.019 592	+140	413.15	0.002 420	0.001 141
-225	48.15	0.020 768	0.017 309	+150	423.15	0.002 363	0.001 103
-220	53.15	0.018 815	0.015 465	+160	433.15	0.002 309	0.001 067
-215	58.15	0.017 197	0.013 948	+170	443.15	0.002 257	0.001 033
-210	63.15	0.015 835	0.012 677	+180	453.15	0.002 207	0.001 000
-205	68.15	0.014 674	0.011 600	+190	463.15	0.002 159	0.000 969
-200	73.15	0.013 671	0.010 675	+200	473.15	0.002 114	0.000 940
-195	78.15	0.012 796	0.009 872	+210	483.15	0.002 070	0.000 912
-190	83.15	0.012 027	0.009 171	+220	493.15	0.002 028	0.000 885
-185	88.15	0.011 344	0.008 552	+230	503.15	0.001 988	0.000 859
-180	93.15	0.010 735	0.008 003	+240	513.15	0.001 949	0.000 834
-175	98.15	0.010 189	0.007 512	+250	523.15	0.001 912	0.000 811
-170	103.15	0.009 695	0.007 072	+260	533.15	0.001 876	0.000 789
-165	108.15	0.009 246	0.006 674	+270	543.15	0.001 841	0.000 767
-160	113.15	0.008 838	0.006 314	+280	553.15	0.001 808	0.000 746
-155	118.15	0.008 464	0.006 003	+290	563.15	0.001 776	0.000 726
-150	123.15	0.008 120	0.005 659	+300	573.15	0.001 745	0.000 707
-140	133.15	0.007 5 10	0.005 158	+310	583.15	0.001 715	0.000 689
-130	143.15	0.006 986	0.004 709	+320	593.15	0.001 686	0.000 67 1
-120	153.15	0.006 530	0.004 322	+330	603.15	0.001 658	0.000 654
-110	163.15	0.006 129	0.003 987	+340	613.15	0.001 631	0.000 647
-100	173.15	0.005 775	0.003 693	+350	623.15	0.001 605	0.000 621
- 90	183.15	0.005 460	0.003 435	+360	633.15	0.001 579	0.000 606
- 80	193.15	0.005 177	0.003 205	+370	643.15	0.001 555	0.000 591
- 70	203.15	0.004 923	0.003 000	+380	653.15	0.001531	0.000 577
- 60	213.15	0.004 692	0.002 816	+390	663.15	0.001 508	0.000 562
- 50	223.15	0.004 481	0.002 65 1	+400	673.15	0.001 486	0.000 548
- 40	233.15	0.004 289	0.002 501	+420	693.15	0.001 443	0.000 5 22
- 30	243.15	0.004 113	0.002 364	+440	713.15	0.001 402	0.000 497
- 20	253.15	0.003 950	0.002 240	+460	733.15	0.001 364	0.000 474
- 10	263.15	0.003 800	0.002 126	+480	753.15	0.001 328	0.000 452
0	273.15	0.003 661	0.002 022	+500	773.15	0.001 293	0.000 431
+ 10	283.15	0.003 532	0.001 926	+520	793.15	0.001 261	0.000 411
+ 20	293.15	0.003 411	0.001 837	+540	813.15	0.001 230	0.000 391
+ 30	303.15	0.003 299	0.001 755	+560	833.15	0.001 200	0.000 373
+ 40	313.15	0.003 193	0.001 678	+580	853.15	0.001 172	0.000 355
+ 50	323.15	0.003 095	0.001 607	+600	873.15	0.001 145	0.000 338

According to Hoffmann and Florin [19].

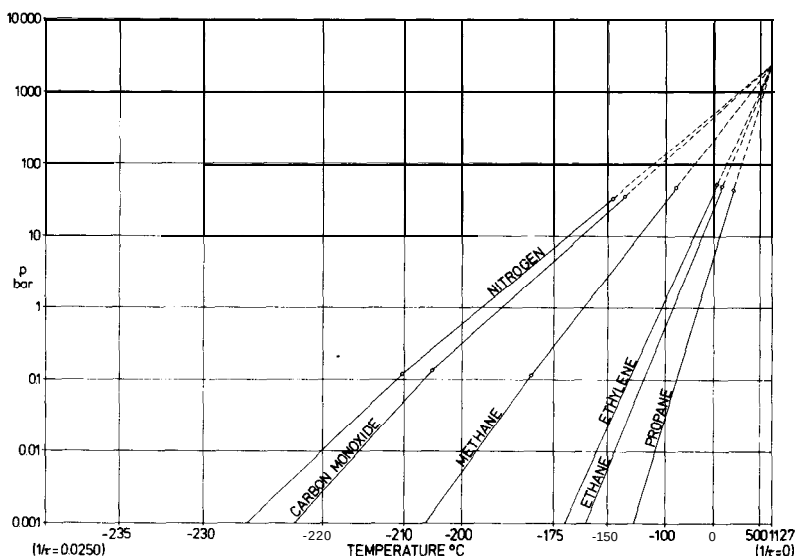


Figure 1 Cox chart [18] prepared according to Hoffmann and Florin [19] for the low-temperature range.

$$\frac{\Delta \tilde{H}_v}{T_b} = \frac{\tilde{R}(-\ln p_{rb})}{1 - T_{rb}} \quad (9)$$

An exact calculation of the heat of vaporization of pure (and mixed) fluids at any temperature is possible by evaluating the **Clausius-Clapeyron** equation:

$$\Delta \tilde{H}_v = T(\tilde{V}_{\text{vap}} - \tilde{V}_{\text{liq}}) \left(\frac{dp}{dT} \right) \quad (10)$$

where dp/dT is the slope of the vapor pressure-temperature curve at the temperature of vaporization. At low pressures, $\tilde{V}_{\text{liq}}$ (the molar volume of the liquid phase) can be neglected in comparison to $\tilde{V}_{\text{vap}}$ (the molar volume of the saturated vapor). If, in addition,

$\tilde{V}_{\text{vap}}$ is taken as the specific volume of the ideal gas (i.e., $Z = 1$), $\tilde{V}_{\text{vap}} = R T/p$, the equation is simplified to

$$\Delta \tilde{H}_v = T \frac{\tilde{R} T}{p} \frac{dp}{dT} = \tilde{R} \frac{T^2}{p} \frac{dp}{dT} = \tilde{R} \frac{d \ln p}{d(1/T)} \quad (11)$$

which is proportional to the slope of the vapor pressure-temperature curve in the $\log p$ versus $1/T$ diagram.

If, in such a plot, the slope of the saturation curve at the boiling point is estimated by drawing a straight line from the boiling point to the critical point, this last expression converts into the **Trouton** parameter given above.

Since the conditions $Z = 1$ and $\tilde{V}_{\text{vap}} \gg \tilde{V}_{\text{liq}}$ are valid only in the low-pressure range, other methods have been

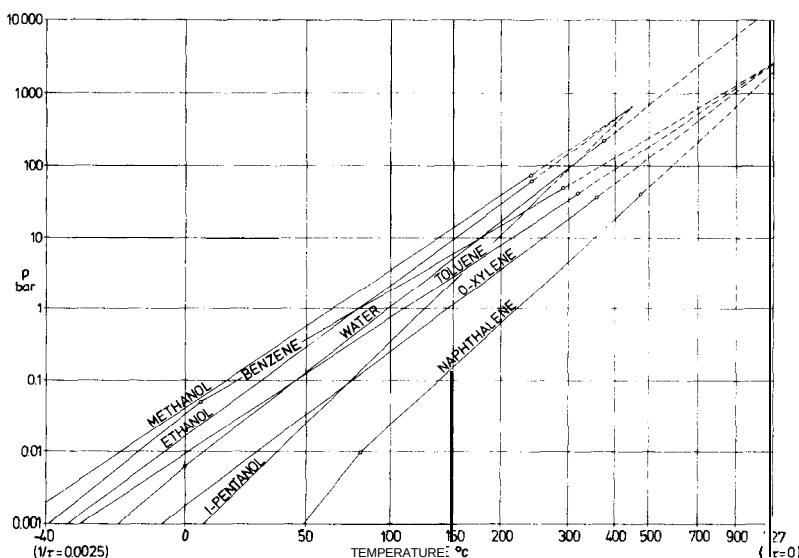


Figure 2 Cox chart [18] prepared according to Hoffmann and Florin [19] for the high-temperature range.

proposed for estimating the heat of vaporization at any temperature. If one value of $\tilde{A}H_v$ is known (e.g., that at the normal boiling point), good results are obtained with the correlation

$$\frac{\Delta\tilde{H}_{v1}}{\Delta\tilde{H}_{v2}} = \left(\frac{1 - T_{r1}}{1 - T_{r2}} \right)^n \quad (12)$$

where $n = 0.38$ for nonassociating liquids, according to a recommendation given by Watson [8].

D. Specific heat capacity

(a) Ideal gases

The specific heat capacity (specific heat) of ideal gases applies to real gases in the range of low (reduced) pressures and high (reduced) temperatures. Roughly this range is limited by $T_r > 2$ for $p_r < 0.4$ and $T_r > 4$ for $p_r < 4$ [see Sec. D(b)]. The order of magnitude for the specific heat at constant pressure, $\tilde{C}_p$, is about 30 kJ/kmol K, increasing with increasing temperature.

According to the kinetic theory of gases, the internal energy of an (ideal) gas is identical with the kinetic energy of its molecules. The possibility of internal vibrations of the atoms within the molecules is neglected as well as the energy of interaction between molecules as a function of their separation distance.

In monatomic gases, the kinetic energy consists merely of translational energy while in polyatomic gases it is evenly distributed between translational energy and energy of rotation. Each of the possible vectors will pick up the same amount of energy: $\tilde{R}/2 = 4\,157\text{ J/kmol K}$.

In ideal gases, the difference between the specific heat capacity at constant pressure, $\tilde{C}_p$, and at constant volume, $\tilde{C}_v$, amounts to

$$\tilde{C}_p - \tilde{C}_v = p \frac{dV}{dT} = \tilde{R} = 8\,314.3\text{ J/kmol K} \quad (13)$$

In consequence, the relationships for ideal gases, according to the kinetic theory, are as follows:

1. Monatomic (three degrees of freedom for translational movement in the three directions of space):

$$\tilde{C}_p = \frac{5}{2} \tilde{R} = 20.8\text{ kJ/kmol K} \quad (14)$$

$$\tilde{C}_v = \frac{3}{2} \tilde{R} = 12.5\text{ kJ/kmol K} \quad (15)$$

2. Diatomic (two additional degrees of freedom for vectors of rotation perpendicular to the connecting line between the two atoms):

$$\tilde{C}_p = \frac{7}{2} \tilde{R} = 29.1\text{ kJ/kmol K} \quad (16)$$

$$\tilde{C}_v = \frac{5}{2} \tilde{R} = 20.8\text{ kJ/kmol K} \quad (17)$$

3. Triatomic (one additional degree of freedom for a vector of rotation in the third possible direction):

$$\tilde{C}_p = \frac{8}{2} \tilde{R} = 33.3\text{ kJ/kmol K} \quad (18)$$

$$\tilde{C}_v = \frac{6}{2} \tilde{R} = 24.9\text{ kJ/kmol K} \quad (19)$$

The real specific heat capacities of monatomic gases sufficiently above the saturation temperature indeed have the values predicted by the kinetic theory of gases. The diatomic and polyatomic gases, however, have higher specific heat capacities because of the elastic vibrations of the molecules neglected by the theory. Such vibrations can be stimulated only by collisions that transmit the minimum quantum of energy, $h\nu$, where h is the Planck quantum ($h = 6.625\,3 \times 10^{-34}\text{ J s}$) and ν is the frequency of the molecule as an elastic vibrator in s^{-1} . With increasing temperature the number of collisions fulfilling this requirement will also increase, thus increasing the proportion of vibrational energy within the total energy of a polyatomic (but still ideal) gas.

In real gases, the forces interacting between the molecules let the difference $\tilde{C}_p - \tilde{C}_v$ exceed $\tilde{R}$ if the distance between the molecules becomes small, i.e., at low temperatures or high pressures.

The specific heat capacity of a polyatomic ideal gas can be calculated from the vibration patterns of its molecules as determined by spectroscopic methods. However, an exact prediction of these patterns from the molecular structure alone is only feasible for very simple molecules. The vibration frequency of a single atom is strongly influenced by the kind of bonds connecting it with its immediate neighbors, but only to a lesser degree by the rest of the structure of the molecule. Thus, typical atomic groups give typical contributions to the specific heat of a polyatomic gas, no matter what other groups are present in the molecule. Benson [23] has developed a very accurate group contribution method also described in [1].

A different method requiring less tabulation has been reported by Sakiadis and Coates [24] and Gambill [25]. Here, a certain frequency is ascribed to the bending vibration and another frequency to the longitudinal vibration of many types of bonds. The real influence of any atom in the molecule on the vibration frequencies of all its atoms is thereby neglected. Nevertheless, the mean deviation is better than $\pm 5\%$ within a temperature range from 200 K to over 1 000 K (or the temperature of decomposition of nearly all organic compounds).

The molar specific heat of an ideal polyatomic gas, $\tilde{C}_{p\text{id}}$, is calculated by the equation

$$\begin{aligned} \frac{\tilde{C}_{p\text{id}}}{\tilde{R}} = & 4 + \frac{n_r}{2} + \sum n_i \Delta_{vi} \\ & + \frac{3z - 6 - n_r - n}{n} \sum n_i \Delta_{\delta i} \end{aligned} \quad (20)$$

where $\Delta_{\nu i} = f(\omega_{\nu i}/T)$ is the contribution of the longitudinal vibration of a certain type of bond

$\Delta_{\delta i} = f(\omega_{\delta i}/T)$ is the contribution of the bending vibration of a certain type of bond

$\omega_{\nu i}$ is the frequency, longitudinal

$\omega_{\delta i}$ is the frequency, bending

n_i = number of bonds of type i

n_r = number of bonds allowing a rotation of one part of a molecule relative to another part, i.e., C-C, O-O bonds, and C-O bonds in ethers and esters

n = total number of bonds in the molecule

z = number of atoms in the molecule

The vibration frequencies ω_i ascribed to various types of organic bonds are listed in Table 3, where the indices ν and δ again denote longitudinal and bending vibrations. $\Delta_{\nu i}$ and $\Delta_{\delta i}$ are functions of $\omega_{\nu i}/T$ and $\omega_{\delta i}/T$, respectively. They are plotted in Fig. 3.

The method is not applicable for strongly associating vapors since they deviate too much from the ideal gas conditions.

Table 3 Bond frequencies and bond increments for estimating specific heat capacities of gases, vapors, and liquids^a

Type of bond	ω_{ν}	ω_{δ}	AG	AL
C-H (aliphatic)	2914	1 274	5.10	4.16
C-C (aliphatic)	989	390	-1.10	1.07
C=C (aliphatic symmetric)	1 618	599	5.68	6.36
C=C (aliphatic asymmetric)	1 664	421	5.68	6.36
C≡C (aliphatic)	2 215	333		
C-H (aromatic)	3 045	1318	5.10	4.16
C-C (aromatic)	989	390	-1.10	1.07
C=C (aromatic)	1618	844	5.68	6.36
C-I	500	260		
C-Br	560	280	15.54	15.33
C-Cl	650	330	12.91	12.55
C-F	1050	530		
c-s	650	330		
c=s	1050	530		
s-s	500	260		
S-H	2570	1 050		
C-N	990	390	0.40	0.24
C=N	1620	845		
N-N	990	390		
N-H	2920	1 320	5.57	5.00
N-O	1030	205		
N=O	1700	390	a.17	8.28
c-o	1030	205	2.05	2.78
c=O	1 700	390	9.93	9.08
O-H	3420	1 150	4.64	5.07
o-o	850	(300)		
Cycle			4.80	-0.43

^aSee Refs. [25, 26].

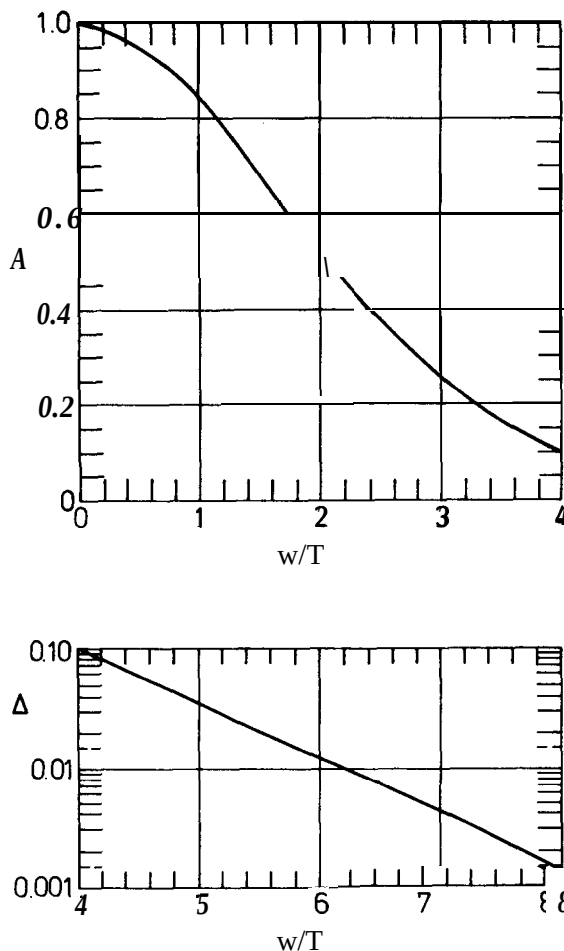


Figure 3 Plot of $A = f(\omega/T)$ for the evaluation of Eqs. (20) and (23). Redrawn from [24].

(b) General fluids

For a real fluid in the whole range of reduced pressures and temperatures, the molar specific heat at constant pressure can be calculated by the equation

$$\tilde{C}_p = \tilde{C}_{p, id} + \Delta\tilde{C}_p \quad (21)$$

The residual specific heat $\Delta\tilde{C}_p$ can be given as a function of the reduced pressure p_r , the reduced temperature T_r , and Pitzer's acentric factor ω :

$$\Delta\tilde{C}_p = \tilde{R}(\Delta_0 + \omega A_1) \quad (22)$$

where A_0 and A_1 are functions of p_r and T_r given in Figs. 4 and 5 [4, 43].

The method is valid in the whole range of p_r and T_r but gives no reliable values in the surroundings of the critical state. Below the critical state, the curves are split up into a liquid range and a vapor range.

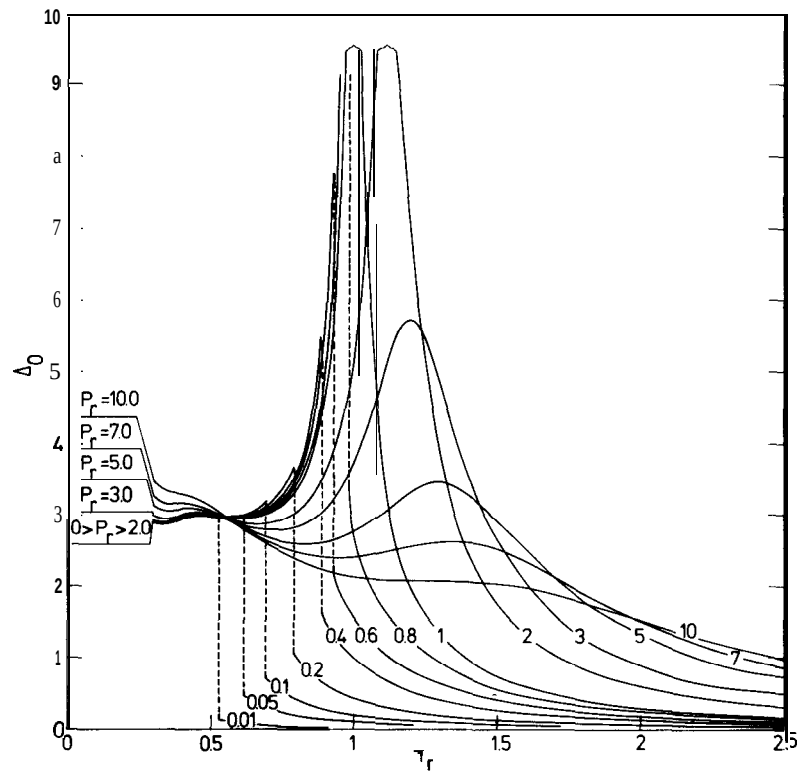


Figure 4 Plot of $\Delta_0 = f(T_r, p_r)$ for the evaluation of Eq. (22). Drawn according to Lee and Kesler [43].

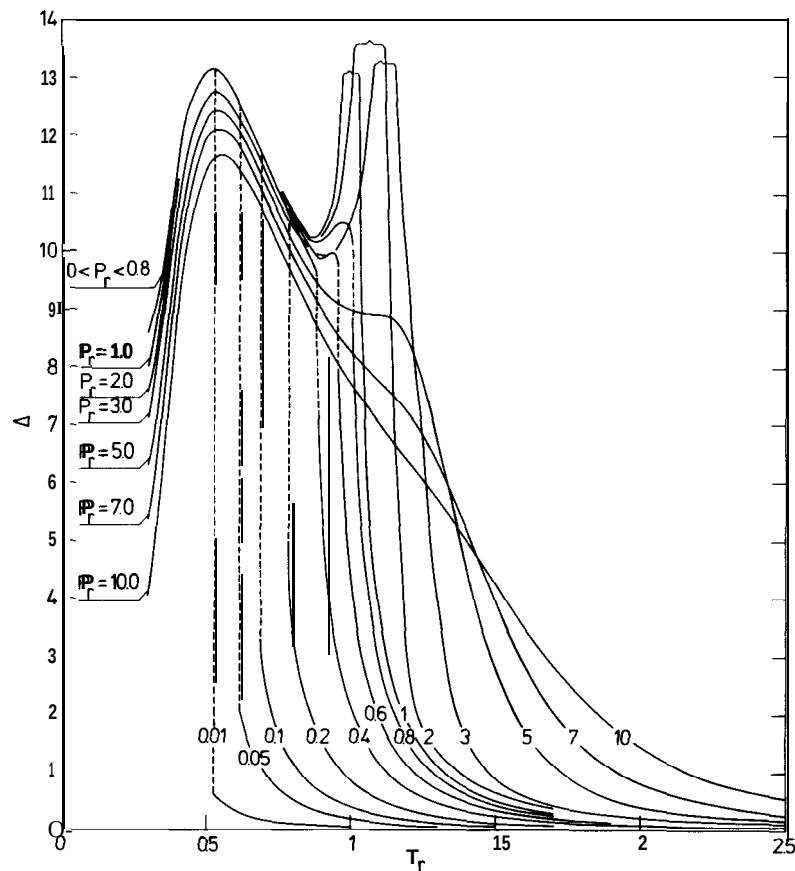


Figure 5 Plot of $A = f(T_r, p_r)$ for the evaluation of Eq. (22). Drawn according to Lee and Kesler [43].

(c) Liquids

The specific heat capacities of liquids below their normal boiling point are usually in the range of

$$1.6 \text{ kJ/kg K} < c_p = \left(\frac{\tilde{C}_p}{\tilde{M}} \right) < 2.1 \text{ kJ/kg K}$$

with exceptions to higher values (water, ammonia up to 4.6 kJ/kg K) and lower values (halogen compounds, down to 0.42 kJ/kg K). In the low-pressure range, the specific heat capacities of liquids rise with temperature. For the estimation a method may be used, according to Sakiadis and Coates [24], which is very similar to the one given in Sec. D(a). The corresponding equation is

$$\frac{C_{p, \text{li}}}{\tilde{R}\kappa} = 6 + n_r + \sum n_i \Delta_{vi} + F \frac{3z - 6 - n_r - n}{n} \sum n_i \Delta_{\delta i} \quad (23)$$

with the same meaning of the symbols as in Sec. D(a), and also employing Table 3 and Fig. 3. Of the additional factors F and κ , F is a correction factor to be taken from Fig. 6, and

$$\kappa = \left(\frac{\sum \Delta G}{\sum \Delta L} \right)^7$$

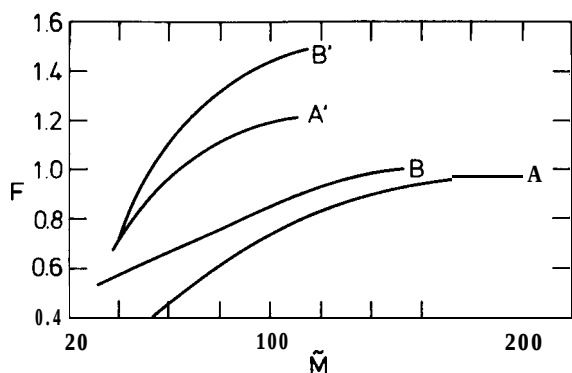


Figure 6 Correction factor F as a function of the molecular mass $\tilde{M}$ to be used in Eq. (23). Redrawn from [24].

Table 4 Values of the constants C and n for the estimation of specific heat capacities of liquids^a

Row	C	n
Alcohols	3 560	−0.10
Acids (organic)	3 800	−0.152
Ketones	2 460	−0.013 5
Esters	2 510	−0.057 3
Amines (aliphatic)	6 820	−0.22
Nitriles (aliphatic)	3 030	−0.073 3
Hydrocarbons (aliphatic)	3 660	−0.113
Hydrocarbons (aromatic)	1 370	+0.048 5
Monochloro- (aliphatic)	640	+0.229
Polychloro- (aliphatic)	19 800	−0.63

^aAccording to Pachaiappan et al. [26].

where AG and AL are added up from the increments given in Table 3.

A relative rotation of one part of a molecule in liquids is only possible with C-C bonds; therefore n_r denotes the number of aliphatic C-C bonds in a molecule. If there are types of bonds in a molecule for which no values of AG and AL are listed in Table 3, then κ is estimated on the basis of the remaining bond increments. Deviations of $\pm 10\%$ are to be expected, especially for the first members of homologous rows or for temperatures below 220 K (-50°C).

Pachaiappan et al. [26] recommend an equation by which the specific heat capacities of members of the same homologous row can be calculated alone from their molecular masses:

$$C_p = C \tilde{M}^n \quad (24)$$

The constants C and n can be evaluated if the specific heat capacity for at least two members of the row are known. For a number of homologous rows Table 4 gives values of C and n . The deviations are mostly within a range of $\pm 5\%$.

Nomenclature for Section 5.1.3 appears at the beginning of Part 5. References appear at the end of Section 5.1.5.

Table 2 Atomic and structural increments for calculating J in Souders' equation for estimating liquid viscosities^a

Atomic and group values					
C	50.2	OH	57.1	CH ₃	55.6
H	2.7	Cl	60.0	c o o	90.0
O	29.7	Br	79.0	COOH	104.4
N	37.0	I	110.0	NO ₂	80.0
Structural values					
Double bond	-15.5	Ortho and para	+ 3.0		
5-C ring	-24.0	Meta	+ 1.0		
6-C ring	-21.0	-CH=CHCH ₂ X	+ 4.0		
Side group on 6-C ring		R>CHX	+ 6.0		
With $M < 17$	- 9.0	(X = negative group)			
With $M > 16$	-17.0				
R>CHCH<R	+ 8.0	R>C<R	+1 .0		
H-C-R	+10.0	CH ₃ -C-R	+ 5.0		

^aSee Ref. [28].

The viscosity η is obtained in N s/m², if the molecular mass $\tilde{M}$ is given in kg/kmol and the density ρ is in kg/m³. The method is adequate for a rough estimation of the viscosity at room temperature for liquids with freezing points below and boiling points above 20° C. It fails completely if sulfur is present in the compound. For other nonassociating liquids the deviation should be in the range of $\pm 30\%$. For acids, the results tend to be too low; for multihalogenated hydrocarbons they are often too high.

For liquids below their normal boiling point, Thomas [29] suggested the equation

$$\log \left(8600 \frac{\eta}{\rho^{1/2}} \right) = \Theta \left(\frac{1}{T_r} - 1 \right) \quad (3)$$

The viscosity η is obtained in N s/m², if the density ρ is

Table 3 Structural increments for calculating Θ in Thomas' equation for estimating liquid viscosities

Double bond	0.478
C ₆ H ₅	0.385
CO in ketones and esters	0.105
CN in nitriles	0.381
S	0.043
C	-0.462
H	0.249
O	0.054
Cl	0.340
Br	0.326
I	0.335

given in kg/m³ and Θ is added up from increments taken from Table 3.

The method is reported to be more accurate than Souders' method described above for aromatics above benzene, unsaturated compounds, and paraffins. It works also with compounds containing sulfur, but gives deviations up to $\pm 80\%$ for multihalogenated compounds, acids, alcohols, aldehydes, amines, naphthenes, and heterocyclic compounds. In judging the accuracy of estimating methods for liquid viscosities one should, however, keep in mind the vast range of possible values which lets a deviation of $\pm 50\%$ still be a good approach.

(c) Temperature dependency of the viscosity of liquids

As already mentioned, the viscosity of liquids decreases rapidly with rising temperature. It may serve as a rule of thumb that within some kelvins above the melting point the viscosity of many liquids is close to 2×10^{-3} N s/m², decreasing to about 0.3×10^{-3} N s/m² at the normal boiling temperature. Within this range of temperatures, the logarithm of the viscosity is an almost linear function of the reciprocal temperature. In approaching the freezing point, however, there is often a sharp rise in viscosity. On the contrary, above the temperature of the normal boiling point, the decrease of the viscosity is usually more rapid than suggested by the logarithmic function valid in the intermediate range.

Following theoretical considerations, Andrade [30] introduced the liquid density into the logarithmic function and thus obtained the equation

$$\eta = 10^{-6} A \rho^{1/3} e^{c\rho/T} \quad (4)$$

The constants A and c of Andrade's equation can be determined if two or more viscosity values, η_1, η_2 , etc., are known at different temperatures, T_1, T_2 , etc., together with the respective liquid densities, ρ_1, ρ_2 , etc.:

$$c = \frac{\ln(\eta_1/\eta_2) + \frac{1}{3} \ln(\rho_2/\rho_1)}{\rho_1/T_1 - \rho_2/T_2} \quad (5)$$

$$A = 10^6 \eta \rho^{-1/3} e^{-c\rho/T} \quad (6)$$

The equation is reported to be a very good approach for inorganic and organic liquids and even for molten metal. It is valid not only between the experimental values but also in extrapolation until close to the critical state. However, the uncertainty of all experimental values must be kept in mind; thus, A and c should not be determined from measured viscosity values too close together. If the liquid is highly associating, the values of c are extraordinarily high at lower temperatures but normalize as the temperature rises—that is, c is no longer a constant for such liquids.

Numerical values of A and c in Andrade's equation

are given in Table 4. They are valid for obtaining η in N s/m^2 if p is in kg/m^3 . The tabulated values are based on experimental viscosity values between 273 and 373 K (0 and 100°C). Within this range, the deviations are

mostly below $\pm 1\%$; for liquids marked with $+$, deviations from $\pm 5\%$ to even $\pm 20\%$ must be expected, however.

Lewis and Squires [31] have developed a chart illustrated in Fig. 2 which shows the approximate change

Table 4 Numerical values for the constants A and c in Andrade's relationships, Eqs. (4) and (7)^a

Compound	A	c	Compound	A	c
Elements			Fluorobenzene	5.14	0.695
Water	0.588	1.534	Chlorobenzene	5.48	0.703
Mercury	24.67	0.021	Iodobenzene	5.47	0.516
Chlorine	11.53	0.197	Sulfur compounds		
Bromine	7.08	0.213	Thiophene	4.40	0.739
Iodine	15.35	0.220	Methyl mercaptan	5.30	0.610
Paraffins			Ethyl mercaptan	5.08	0.779
Pentane	4.34	0.855	Carbon disulfide	7.29	0.356
Hexane	4.55	0.929	Alcohols		
Heptane	4.53	0.990	Methanol	2.69	1.171
Octane	4.37	1.098	Ethanol	2.28	1.491
i-Pentane	4.36	0.856	Propanol	1.05	1.986
i-Hexane	4.54	0.900	Butanol	0.783	2.174
i-Heptane	4.49	0.974	Allyl alcohol	1.33	1.609
Aromatic compounds			i-Propanol	0.352	2.466
Benzene	3.38	1.000	i-Butanol ^b	0.34	0.262
Ethyl benzene	4.58	0.922	Dimethyl ethylcarbinol ^b	0.097	3.111
o-Xylene	4.17	1.007	Trimethyl carbinol ^b	0.039	3.574
m-Xylene	4.65	0.893	Amyl alcohol, active	0.298	2.688
p-Xylene	4.36	0.931	Inactive	0.515	2.640
Toluene	4.39	0.912	Acids and anhydrides		
Olefins			Formic acid	2.25	1.036
Isoprene	4.49	0.731	Acetic acid	4.28	0.927
1,5-Hexadiene	4.16	0.854	Acetic anhydride	4.57	0.809
Trimethyl ethylene	4.70	0.721	Propionic acid	5.13	0.904
Halogen compounds			Propionic anhydride	4.18	0.952
Propyl chloride	5.02	0.655	Butyric acid	4.19	1.107
i-Propyl chloride	4.59	0.683	i-Butyric acid	4.55	1.048
i-Butyl chloride	4.43	0.797	Esters		
Allyl chloride	4.78	0.611	Methyl formate	5.24	0.571
Methylene chloride	5.77	0.422	Ethyl formate	4.92	0.675
Ethylene chloride	4.44	0.668	Propyl formate	4.51	0.799
Ethylidene chloride	4.98	0.557	Methyl acetate	4.63	0.668
Chloroform	6.07	0.412	Ethyl acetate	4.40	0.767
Carbon tetrachloride	3.97	0.560	Propyl acetate	4.06	0.891
Ethylene tetrachloride	6.80	0.436	Methyl propionate	4.98	0.719
Ethyl bromide	5.46	0.378	Ethyl propionate	4.33	0.838
Propyl bromide	5.27	0.473	Methyl butyrate	4.25	0.862
i-Propyl bromide	4.91	0.492	Methyl i-butyrate	4.37	0.827
i-Butyl bromide	4.80	0.605	Ethers		
Allyl bromide	5.08	0.444	Diethyl ether	4.44	0.571
Acetylene bromide	6.52	0.315	Methylpropyl ether	4.46	0.675
Propylene bromide	4.73	0.505	Ethylpropyl ether	4.25	0.843
i-Butylene bromide	3.76	0.656	Dipropyl ether	4.14	0.951
Ethylene bromide	4.79	0.446	Methyl i-butyl ether	4.34	0.825
Methyl iodide	5.40	0.247	Ethyl i-butyl ether	4.12	0.925
Ethyl iodide	5.68	0.319	Carbonyl compounds		
Propyl iodide	5.43	0.406	Acetaldehyde	4.80	0.610
i-Propyl iodide	5.30	0.410	Acetone	4.91	0.720
i-Butyl iodide	4.90	0.499	Methylethyl ketone	4.53	0.834
Allyl iodide	5.23	0.389	Diethyl ketone	4.76	0.848
			Methylpropyl ketone	4.72	0.884

^aSee Ref[30].

^bFor these compounds deviations greater than $\pm 5\%$ are to be expected.

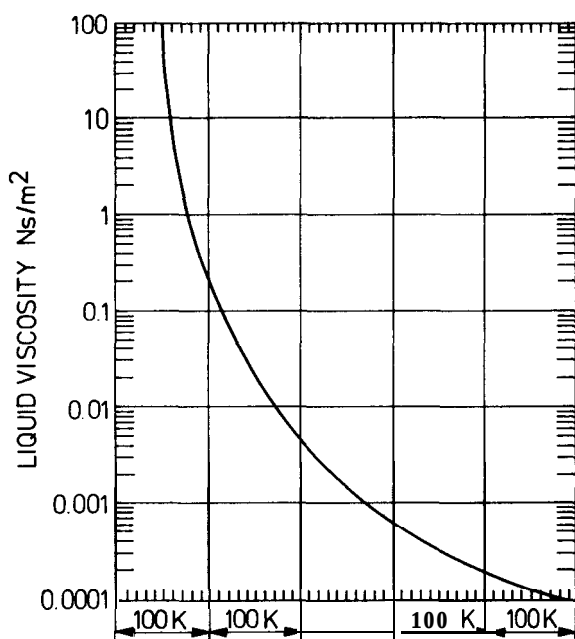


Figure 2 Change of liquid viscosity with temperature. Adapted from Lewis and Squires [31].

of viscosity with temperature for many fluids, except mercury but including water. To use this chart, one enters with a known viscosity value and follows the curve for a distance according to the temperature change in question.

For petroleum oils, the use of the **ASTM Viscosity-Temperature Chart for Liquid Petroleum Products** (ASTM D 341-39) is recommended.

(d) Pressure dependency of the viscosity of liquids

The viscosity of all liquids increases with pressure. Most data suggest that the logarithm of η is an almost linear function of pressure in a range of 1 000 to 4 000 bars. For water and mercury, the increase of viscosity is very little, especially at lower temperatures. For oils, Bondi [32] observed that, as a rule of thumb, an increase in pressure of 100 bars has about the same effect on viscosity as a decrease in temperature of 3 K.

The pressure dependency of viscosity is higher for liquids with high initial viscosity and for liquids with more branched molecules. Other influences are the liquid density and its change with pressure, i.e., the liquid compressibility. Andrade [30] gave the relationship

$$\frac{\eta_p}{\eta_0} = \left(\frac{\rho_p}{\rho_0} \right)^{1/6} \left(\frac{\kappa'_0}{\kappa'_p} \right)^{1/2} e^{c(\rho_p - \rho_0)/T} \quad (7)$$

where the subscripts $p, 0$ denote high pressure and low pressure conditions; κ is the isothermal compressibility

$\kappa' = 1/\tilde{V}(\partial\tilde{V}/\partial p)_T$ which can be estimated [e.g., from Fig. 5.1.2(3)] if no measured values are available. [Since Fig. 5.1.2(3) gives Z as a function of p_r , one has to calculate

$$\frac{1}{\tilde{V}} \left(\frac{\partial\tilde{V}}{\partial p} \right)_T = -\frac{1}{p} \left(\frac{\partial Z}{\partial p} \right)_T = -\frac{1}{p^2} \frac{1}{p_r} \left(\frac{\partial Z}{\partial p_r} \right)_T \quad (8)$$

where $(\partial Z/\partial p_r)_T$ is the slope of the curve and $T_r = \text{const}$ at p_r and T_r of interest.] For c see Sec. A(c).

B. Thermal conductivity

(a) Thermal conductivity of gases

With the exceptions of hydrogen ($\lambda = 0.18$ W/m K at 300 K) and helium ($\lambda = 0.15$ W/m K at 300 K) the thermal conductivities of gases and vapors are in the range $0.01 < \lambda < 0.025$ W/m K. The thermal conductivity of gases is explained by the kinetic theory as the exchange of energy in collisions between the molecules of a gas. Therefore, λ is related to the heat capacity per unit volume of the gas, $\tilde{C}_v/\tilde{V}$, the average particle velocity v , and the mean free path l :

$$\lambda = \frac{1}{3} \frac{C_v}{\tilde{V}} v l \quad \text{W/m K} \quad (9)$$

Usually, v and l are not available, but there is a close relationship between thermal conductivity λ and viscosity η . According to the kinetic theory of gases, the dynamic (absolute) viscosity is

$$\eta = \frac{1}{3} \rho v l = \frac{1}{3} \frac{\tilde{M}}{\tilde{V}} v l \quad \text{N s/m}^2 \quad (10)$$

Therefore, the following relationship should be valid:

$$\lambda = \eta \frac{C_v}{\tilde{M}} \quad \text{W/m K} \quad (11)$$

In reality, however, a correction of this relationship is required in order to get agreement with measured values. Based on theoretical considerations, but with simplifying assumptions, Eucken [33] proposed the following correction:

$$\lambda = \frac{\tilde{C}_v}{\tilde{M}} \frac{9\kappa - 5}{4} \quad (12)$$

where $\kappa = \tilde{C}_p/\tilde{C}_v$. Thus, Eucken's correction factor ideally should have the following values:

Monatomic gases: $\kappa = 1.67$; $(9\kappa - 5)/4 = 2.50$

Diatomic gases: $\kappa = 1.40$; $(9\kappa - 5)/4 = 1.90$

Triatomic gases: $\kappa = 1.33$; $(9\kappa - 5)/4 = 1.74$

Polyatomic gases: $\kappa \rightarrow 1.0$; $(9\kappa - 5)/4 \rightarrow 1.0$

Eucken's relationship gives a good approach in the pressure range from about 0.1 to 10 bars and in the temperature range from about 80 to 1 000 K. The

calculated values seem to give a lower limit for actual values, but the deviations are normally less than -20%.

(b) Temperature dependency of the thermal conductivity of gases

In the range of low pressures, the thermal conductivity of gases increases with temperature. For monatomic and diatomic gases, the rise in conductivity is almost proportional:

$$\frac{\lambda_2}{\lambda_1} = \frac{T_2}{T_1} \quad (13)$$

For organic vapors, Owens and Thodos [34] recommend the relationship

$$\frac{\lambda_2}{\lambda_1} = \left(\frac{T_2}{T_1} \right)^m \quad (14)$$

with $m = 1.786$.

(c) Pressure dependency of the thermal conductivity of gases

With increasing pressure, the thermal conductivity of gases will also increase. At very low pressures (i.e., in the vacuum below about 0.01 bar), the mean free path is partly or wholly limited by the walls confining the gas volume in question. In that range, the thermal conductivity increases linearly with pressure. Above, the increase of λ with pressure slows down considerably. At atmospheric pressure, the increase is in the order of magnitude of 1% per 1 bar of increase in pressure.

For a survey, a plot prepared by Schaefer and Thodos [35] for diatomic gases may be used (see Fig. 3). Note that this plot resembles very much, but is not identical, to Fig. 1.

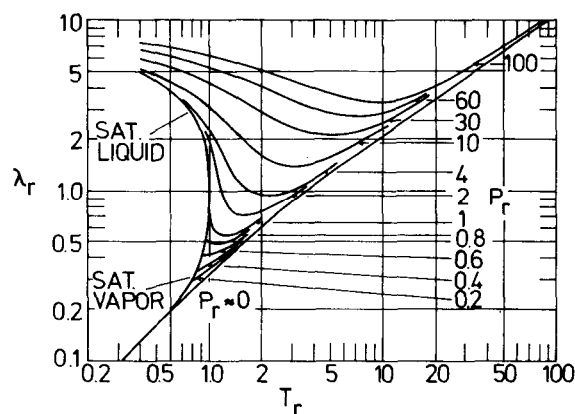


Figure 3 Reduced thermal conductivity $\lambda_r = \lambda/\lambda_c$ for diatomic gases as a function of T_r and p_r from Schaefer and Thomas [35].

Table 5 Structural increments ΔX for estimating the thermal conductivity of liquids'

Atomic group	Δh	
Unbranched hydrocarbons: Paraffins, olefins, cyclic	0	
Branches:		
CH ₃	Each	1
C ₂ H ₅ -, i-C ₃ H ₇ -, C ₄ H ₉ -	Each	2
Substitutions:		
F- and Cl-	Each	1
	Maximum	3
Br-	One	4
	Two	6
I	One	5
OH-iso	Each	1
Normal normal	One	-1
Normal	Two	0
Tertiary	One	5
Oxygen:		
-C=O (ketones, aldehydes)	0	
-C-O (acids, esters)	0	
-O- (ethers)	2	
NH ₂ -	Each	1

From Robbins and Kingrea [37].

(d) Thermal conductivity of liquids

The thermal conductivity of liquids varies within a much wider range than that of gases. Typical values are:

Organic liquids:	$0.12 < \lambda < 0.20 \text{ W/m K}$
Water and other polar liquids:	$0.20 < \lambda < 0.60 \text{ W/m K}$
Salt molten:	$1.0 < \lambda < 4.0 \text{ W/m K}$
Metal molten:	$10 < \lambda < 100 \text{ W/m K}$

At the melting point, the thermal conductivity of many fluids will drop by 15%30% from its value in the solid state. With increasing temperature, the thermal conductivity decreases further. For organic fluids, some equations are recommended by various authors, all based upon a fundamental equation given by Weber [36]:

$$\lambda = a \tilde{C}_p \tilde{V}^{-4/3} \quad (15)$$

[Dimensions for Eq. (15) are given below.] If accuracy is not required (deviations range from $\pm 1.5\%$ up to $\pm 50\%$), Weber's original value of $a = 3.59 \times 10^{-5}$ may be used. For a better estimate of the constant a , Robbins and Kingrea [37] employ a structural constant $\Sigma \Delta h$ which is added up from structural increments listed in Table 5, and use the following relationship:

$$a = 10^{-4} \frac{(36.8 - 2 \Sigma \Delta h)(0.55/T_r)}{(\Delta \tilde{H}_v/T_b) + ii \ln(273/T_b)} \quad (16)$$

The factor $0.55/T_r$ is to be replaced by 1.0 for liquids

with densities $\rho = 1\,000\text{ kg/m}^3$ and higher. The method fails for compounds containing sulfur.

Weber's equations are not dimensionless; i.e., the given constants apply for λ in W/m K, C_p in kJ/kmol K, $\Delta\tilde{H}_v$ in kJ/kmol, $\tilde{V}$ in m^3/kmol , and $R = 8.314\,3\text{ kJ/kmol K}$. The index b stands for the normal boiling point.

(e) Influence of temperature and pressure on the thermal conductivity of liquids

The thermal conductivity of liquids generally decreases with rising temperature up to temperatures well above T_c , i.e., in the range of hypercritical fluids. (Compare also the liquid and hypercritical range in Fig. 3.) In a range sufficiently below the critical temperature, the order of magnitude of this decrease is about 1% per 10 K of increase in temperature. With rising pressure, there is a slight increase of thermal conductivity. Up to pressures of about 50 bars, this effect is negligible, especially at low temperatures. However, the influence of pressure increases in approaching the critical temperature.

C. Prandtl number

(a) Prandtl number of gases

In the range of low pressures, and at temperatures between 200 and 1000 K (-80 – 700°C), the Prandtl number is, according to Eucken [33],

$$\text{Pr} \equiv \frac{\tilde{C}_p \eta}{M \lambda} \approx \frac{4}{9 - 5/\kappa} \quad \text{with } \kappa = \frac{C_p}{\tilde{C}_v} \quad (17)$$

In the given range, it follows that

For monatomic gases:	$\kappa = 1.67$, $\text{Pr} = 0.67$
For diatomic gases:	$\kappa = 1.40$, $\text{Pr} = 0.73$
For triatomic gases:	$\kappa = 1.33$, $\text{Pr} = 0.76$
For polyatomic gases:	$\kappa \rightarrow 1.0$, $\text{Pr} \rightarrow 1.0$

For estimating Prandtl numbers at higher pressures and temperatures, one should try to determine C_p, η , and λ separately.

(b) Prandtl numbers of liquids

If for a liquid, no exact values of C_p, η , and λ are available, the calculation of Pr from estimated values can sometimes be very inaccurate. In such cases, the relationship

$$\log \text{Pr} = 0.0270 \frac{\Delta\tilde{H}_v}{T} - 1.80 \quad (18)$$

given by Gambill [38] could be used for a comparison. This relationship is valid for all practical purposes; deviations above $\pm 50\%$ are to be expected however. For water, Gambill reports slightly different values to give a better correlation:

$$\log \text{Pr} = 0.0244 \frac{\Delta\tilde{H}_v}{T} - 2.20 \quad (19)$$

The equations are valid for T in K, $\Delta\tilde{H}_v$ (at T) in kJ/kmol, while $\log \text{Pr}$ denotes the decimal logarithm of the Prandtl number.

Nomenclature for Section 5.1.4 appears at the beginning of Part 5. References appear at the end of Section 5.1.5.

5.1.5

Surface tension

M. Schunck

A. Methods for estimating the surface tension from physical properties of the fluid

The molecules in the boundary layer between a liquid and its vapor are subject to different attractive forces due to the different densities in the liquid and in the gaseous phase. Obviously, the attraction toward the bulk of the liquid phase is normally much higher than toward the vapor. Thus, the surface resists any increase in area, or in other words, it requires mechanical work to bring a molecule from the bulk of the liquid into the boundary layer.

The surface tension σ is normally defined as the force per unit length in the plane of the surface, measured in N/m. The same result is obtained if σ is defined as the mechanical work (N m = J) necessary to increase the surface by the unit of area (m²). The order of magnitude of the surface tension for various substances are:

Organic and inorganic liquids:	$0.01 < \sigma < 0.06$ N/m
Molten salt	$0.10 < \sigma < 0.20$ N/m
Metal melts	$0.30 < \sigma < 1.00$ N/m

where 1 N/m = 10³ dynes/cm.

For the surface tension of nonassociating liquids at their normal boiling point, Walden [39] gave the simple equation

$$\sigma_b = 0.0656 \times 10^{-6} \left(\frac{\Delta \tilde{H}_{v,b}}{\tilde{V}_b} \right) \quad (1)$$

in N/m, if $\Delta \tilde{H}_{v,b}$ (the heat of vaporization at the normal boiling point) is given in kJ/kmol and $\tilde{V}_b$ (the specific

volume of the liquid phase at the normal boiling point) in m³/kmol.

Also, for nonassociating liquids, Riedel [3d] gives

$$\sigma = 10^{-3} (0.133 \alpha_c - 0.281) (1 - T_r)^{11/9} T_c^{1/3} p_c^{2/3} \quad (2)$$

in N/m, if T_c is in K and p_c in bars. The critical parameter,

$$\alpha_c \equiv \left(\frac{\partial \ln p_r}{\partial \ln T_r} \right)_c$$

can be estimated according to Sec. 5.1.1 E.

For associating liquids, the values obtained by this equation tend to be too high so Hakim et al. [40] recommend at $T_r = 0.6$ (which is usually not far from the normal boiling point) the equation

$$\sigma_{0.6} = 10^{-3} p_c^{2/3} T_c^{1/3} (0.1574 + 0.359 \omega - 1.769 x - 0.51 \omega^2 - 13.69 x^2 + 1.298 \omega x)$$

where ω is the acentric factor (see Sec. 5.1.1 E) and x is the Stiel polar factor

$$x = \log p_{r(0.6)} + 1.70 \omega + 1.552$$

where $\log p_{r(0.6)}$ is the decimal logarithm of the reduced pressure at a reduced temperature of $T_r = 0.6$.

If the surface tension at a certain temperature is known, the transition to a different temperature follows from Riedel's equation above:

$$\frac{\sigma_1}{\sigma_2} = \left(\frac{1 - T_{r,1}}{1 - T_{r,2}} \right)^m$$

with $m = 11/9 = 1.22 \dots$ for nonassociating liquids.

Table 1 Structural increments for the calculation of the Parachor P^a

Atomic group	$\Delta P \times 10^3$	Atomic group	$\Delta P \times 10^3$
Elements		Special groups	
C	1.60	—COO—	11.35
H	2.76	—COOH	13.13
O	3.56	—OH	5.30
N	3.11	—O—	3.56
S	8.73	=O (ketone)	
P	7.20	3 C atoms	3.97
F	4.64	4 C atoms	3.56
Cl	9.82	5 C atoms	3.29
Br	12.09	6 C atoms	3.08
I	16.06	—CHO	11.74
Hydrocarbons		—NH ₂	7.56
CH ₃ —	9.87	—NO ₂ (nitrite)	13.16
CH ₃ —CH(CH ₃)—	23.11	—NO ₂ (nitrate)	16.54
—CH ₂ —	7.11	—CO(NH ₂)	16.31
More than 12 —CH ₂ —	7.17	Additional increments	
CH ₃ —CH ₂ —CH(CH ₃)—	30.57	Ethylene linkage	
CH ₃ —CH ₂ —CH ₂ —CH(CH ₃)—	37.65	terminal	3.40
CH ₃ —CH(CH ₃)—CH ₂ —	30.82	2,3 Position	3.15
CH ₃ —CH ₂ —CH(C ₂ H ₅)—	37.26	3,4 Position	2.90
CH ₃ —C(CH ₃) ₂	30.31	Triple bond	7.22
CH ₃ —CH ₂ —C(CH ₃) ₂	36.91	Ring closure	
CH ₃ —CH(CH ₃)—CH(CH ₃)—	36.98	3-Membered	2.22
CH ₃ —CH(CH ₃)—C(CH ₃) ₂ —	43.31	4-Membered	1.07
C ₆ H ₅ —	33.72	5-Membered	0.53
		6-Membered	0.14

According to Sugden[41] and Quale [42].

According to Hakim et al. [40], the exponent m for associating liquids has the value

$$m = 1.21 + 0.538 \omega - 14.61 x - 1.65 \omega^2 - 32.07 x^2 + 22.03 \omega x$$

with ω and x as given above.

B. Method for estimating the surface tension from the chemical structure

Walden [39] describes an additive method of estimating the surface tension based on numbers and types of bonds in a compound. The most successful additive

method has been established by Sugden [41] and further developed by Quale [42].

In the equation

$$\sigma^{0.25} = P \left(\frac{1}{\tilde{V}_L} - \frac{1}{\tilde{V}_G} \right)$$

the Parachor P is added up from structural increments given in Table 1. In this table, the original values from Quale [42] have been multiplied by $1000^{-1.25} = 0.1779 \cdot 10^{-3}$ in order to give σ in N/m instead of dm^3/kmol . L and G denote the liquid and gas phase. The average deviations to be expected are $\pm 3\%$ with maximum deviations up to $\pm 20\%$.

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5.2

Properties of mixtures of fluids

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5.2.1

Phase behavior of mixtures

R. N. Maddox

A. Introduction

Liquid mixtures can take on a wide variety of characteristics. They can range from a simple, ideal, two-component mixture such as that formed by isobutane and normal butane, through a binary mixture with strongly **nonideal** behavior such as ethyl alcohol and water or acetone and water, to a boiling range cut of a crude oil that has a composition so complex that it is not normally identified in terms of mole fractions of pure components. Because of these widely diverse characteristics, liquid mixtures seldom are amenable to simple rules in prediction of their characteristics. In addition, the rules that work for one kind of mixture probably will not work well for another. In many of the cases that follow there will be different estimating techniques recommended for different kinds of mixtures.

In the world of design today there is heavy dependence on the digital computer for developing property information and for carrying out many of the design calculations. Techniques for carrying out these calculations will be discussed briefly. Attention will also be directed to calculations that can be carried out with a hand calculator or slide rule and give reasonably compatible results with the more-detailed computer calculations.

Gibbs [1] was the first to propose criteria for establishing the equilibrium state. His phase rule is:

$$F + P = C + 2 \quad (1)$$

where F = number of degrees of freedom for the system

P = number of phases present

C = number of components or chemical constituents present,

2 = constant needed when considering both temperature and pressure as variables

The principles of the phase rule apply equally well to single components and to mixtures. In addition, it can be used [2-4] to describe steady-state systems that are not really in thermodynamic equilibrium.

In engineering work many different kinds of systems are encountered. In spite of the fact that there may be liquid-liquid, liquid-liquid-gas, and **solid-liquid-gas** systems, the combination of overriding importance in most processing applications is vapor-liquid equilibrium. In working with vapor-liquid equilibrium one immediately encounters two broad categories: hydrocarbons and nonhydrocarbons. The engineer working with hydrocarbon systems, almost by the nature of his systems, is working with multicomponent mixtures. Rare, indeed, is the hydrocarbon design situation where either a pure component or binary mixture is of prime importance.

On the other hand, the engineer involved with chemicals, even petrochemicals, frequently has only two components and rarely encounters more than three with major composition constituency. For this reason, the fundamental approaches utilized in the two sectors tend to be different. For this reason also, much of the following discussion will be divided between hydrocarbon and chemical systems.

While Eq. (1) enables the engineer to specify the necessary number of variables to make certain that the system is in equilibrium, it does not provide much additional information. Gibbs also formulated the free energy and suggested that at thermodynamic equilibrium the free energy for a given system was at a minimum. This concept has calculational value and has been used for both physical operations and chemically reacting systems. Because of the sheer volume of calculations involved, it is suitable only for digital-computer solution and in no way can be considered to be a tool for hand calculation. However, in complex systems such as encountered in a Claus unit, which produces sulfur from hydrogen sulfide [5], the concept of minimum free energy for the system provides a means for estimating compositions at the equilibrium state. It has been used also for systems in physical equilibrium such as in vapor-liquid flash calculations.

B. Vapor-liquid equilibrium

In vapor-liquid equilibrium, the overall composition of the mixture is generally known. The problem is to relate the instantaneous vapor and liquid compositions to the overall composition in such a way that both a material balance and the criteria for thermodynamic equilibrium are satisfied.

Frequently, the vapor and liquid will not actually be in equilibrium. However, in most cases, evaluation of properties at the equilibrium state will be sufficiently close for engineering needs. The criterion for equilibrium in a vapor-liquid mixture is

$$f_{iv} = f_{il} \quad (2)$$

where f = fugacity ($\bar{F}_i = RT \ln f_i$). For an ideal gas, $f_i = cP$. For a real gas,

$$\lim_{P \rightarrow 0} \frac{f_i}{P} = 1.0$$

$\bar{F}$ = partial molal free energy

c = constant

v = vapor

l = liquid

i = any component

Equation (2) applies individually to each component in the mixture, whether there be two or twenty. The problem of predicting phase compositions resolves into relating the fugacities for each component to mixture compositions. This discussion will concentrate on primary variables-temperature, pressure, composition, etc. Such things as nuclear interference, gravitational or magnetic effects, etc., will be neglected. These things come up only in rare instances and are beyond the scope of this treatment.

According to the law of ideal solutions, the fugacity for a component in the vapor can be expressed as

$$f_{iv} = f_{il}^0 \tilde{y}_i \quad (3)$$

For the same component in the liquid phase:

$$f_{il} = f_{il}^0 \tilde{x}_i \quad (4)$$

where f_{il} = fugacity of component i in the liquid mixture

f_{iv} = fugacity of component i in the vapor mixture

f_{il}^0 = fugacity of component i in the pure liquid state

f_{iv}^0 = fugacity of component i in the pure vapor state

Study of Eqs. (3) and (4) immediately discloses a potential problem: not all components in the mixture may exist in the pure liquid state at the conditions of the mixture. Indeed, this does present a serious problem in many hydrocarbon cases where the lightest component in the mixture may be well above its critical temperature.

Because the fugacity is an unbounded variable, different relationships are ordinarily used for correlation purposes. The fugacity coefficient is such a different variable, a bounded variable, always falling between 0 and 1.0.

An alternative form of Eq. (3) for the vapor phase is developed using the fugacity coefficient:

$$\gamma_{gi} = \frac{f_{iv}}{\tilde{y}_i \pi} \quad (5)$$

where $\tilde{y}$ = composition of the vapor phase

π = total pressure on the system

γ_{gi} = fugacity coefficient

By definition, $\gamma \rightarrow 1.0$ as $\pi \rightarrow 0$. This must be true for all components in the mixture. The actual value of π when γ_{gi} becomes close enough to 1.0 to be considered unity depends upon the nature of the system. For most hydrocarbon mixtures, at temperatures near the normal boiling point, this pressure is less than 100-150 psi. For mixtures containing associating materials (acetic acid-water), there may be significant departure of the **fugacity** coefficient at pressures much less than 1 atm.

For a component in the liquid phase an alternative is to use the activity coefficient which is defined as

$$\gamma_{li} = \frac{a_i}{\tilde{x}_i} \quad (6)$$

where a_i is the activity of component i in the liquid phase. The activity coefficient can also be related to the standard state fugacity by

$$\gamma_{li} = \frac{f_{il}}{\tilde{x}_i} \frac{f_{il}^0}{f_{il}^0} \quad (7)$$

The standard state fugacity f_{i1}^0 is defined at an arbitrarily chosen pressure and composition. Unfortunately, many workers do not clearly **define** their standard state for f_{i1}^0 and this tends to minimize the contribution of their work.

Most equilibrium constant evaluations from the fugacity-activity coefficient basis are developed from one of the following expressions:

$$K = \frac{f_{i1}/\tilde{x}_i}{f_{i0}/y_i} \frac{1}{\pi} \quad (8)$$

$$K = \frac{f_{i1}/P^0 \tilde{x}_i}{f_{i0}/\pi \tilde{y}_i} \frac{P^0}{\pi} \quad (9)$$

$$K = \frac{f_{i1}/f_{i1}^0 \tilde{x}_i f_{i1}^0}{f_{i0}/\pi \tilde{y}_i} \quad (10)$$

$$K = \frac{\gamma_{i1} v_i}{\gamma_{gi}} \quad (11)$$

where π = total system absolute pressure

P^0 = pure component vapor pressure

γ_{i1} = activity coefficient of any component in the liquid mixture

f_{i1} = fugacity of a pure liquid at system conditions

f_{i1}^0 = fugacity of any component as a pure liquid

γ_{gi} = fugacity coefficient of any component in the vapor mixture

As a matter of interest, Chao and Seader [6] used Eq. (11) for prediction of equilibrium constants and enthalpies. Their correlation was the first equilibrium constant correlation developed with the express intent of being used on a digital computer for phase equilibrium generation. They used the Pitzer acentric factor [7] as a third correlating parameter in their corresponding states-type approach.

C. Hydrocarbon phase behavior

In estimating mixture properties there are a number of characteristics of the mixture that can be used. Such characteristics as critical temperature, critical pressure, acentric factor, etc. are frequently referred to as correlating parameters. Estimating the correlating parameters for nearly ideal mixtures made up of light hydrocarbons is exceedingly difficult. Most often the critical temperature and critical pressure for a mixture are estimated as the Kay's rule or mole fraction average values; also referred to as pseudocritical temperature or pressure:

Critical temperature

$$T_{cm} = \sum \tilde{x}_i T_{ci} \quad (12)$$

Critical pressure

$$P_{cm} = \sum \tilde{x}_i P_{ci} \quad (13)$$

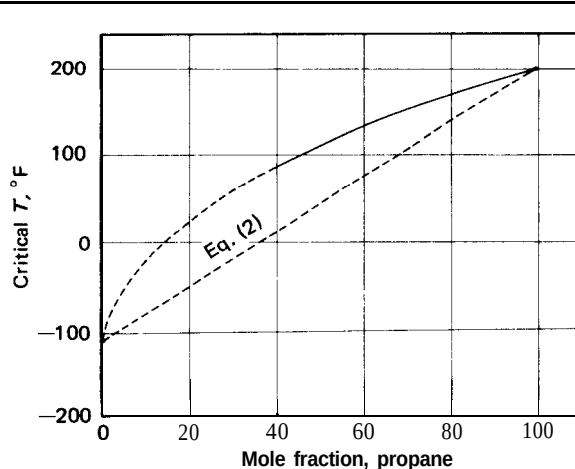


Figure 1 Composition-critical temperature diagram for methane-propane binary.

Equations (12) and (13) assume a linear relationship between composition and the critical property in question. Actual behavior is demonstrated by Figs. 1 and 2 for the methane-propane binary mixture. Data for preparation of the two figures were taken from Katz et al. [8]. Deviation of the critical temperature as shown in Fig. 1 does not appear to be particularly significant. However, as shown in Fig. 2 the influence of this deviation on the critical pressure causes significant deviations from the mole fraction average. The values used to calculate the correlating parameters are so different from the true values that there is good reason for significant error to show up in values calculated through correlations.

The acentric factor was defined by Pitzer et al. [9] as

$$\omega = -(\log P_r^0 - 1)_{T_r=0.7} \quad (14)$$

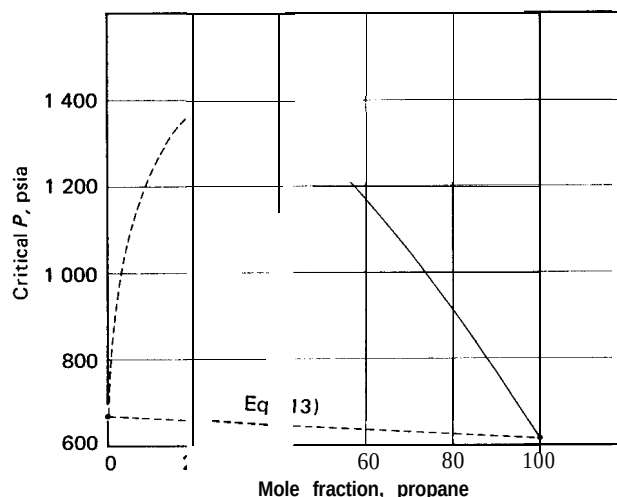


Figure 2 Composition-critical pressure for methane-propane binary.

where P_r^0 = reduced vapor pressure = P^0/P_c

ω = acentric factor

P^0 = vapor pressure in pascals

Edmister [10] showed that, when vapor pressure data are not available, the acentric factor can satisfactorily be approximated by

$$\omega = \frac{3}{7} \frac{\log [P_c / (1.01325 \times 10^5)]}{T_c/T_b - 1.0} - 1 \quad (15)$$

where P_c = critical pressure in pascals

T_c = critical temperature in K

T_b = normal boiling point in K

There are many instances in which the vapor-liquid behavior of mixtures is of importance in heat transfer calculations. While the boiling point of a pure component is a **fixed** temperature at given pressure, this is not true for mixtures. The range of temperatures at which boiling/condensation can occur at a given pressure is dependent on the composition. Figure 3 shows a pressure-temperature diagram for a typical mixture of light hydrocarbons. The overall composition of the mixture whose behavior is depicted in Fig. 3 is constant. The composition of the vapor and liquid phases will change from point to point if, indeed, they do exist. Examination of Fig. 3 immediately discloses some significant differences between mixture and pure component behavior. The critical temperature for a pure component is defined as that temperature above which the material cannot be liquefied. Obviously this **definition** does not apply to the mixture whose behavior is depicted in Fig. 3. There is quite a range of temperatures higher than the critical temperature at which some liquid can exist in equilibrium with the vapor. For a pure component the critical pressure represents the maximum vapor pressure that the component can exert. The

maximum pressure of the two-phase envelope on Fig. 3 exceeds the critical pressure by an amount that depends on the shape of the curve.

Defining the critical temperature for a mixture requires dependence on observations and experimental evidence. On pressure-temperature diagrams such as shown in Fig. 3, lines of constant percentage liquid tend to converge to the point thought to represent the critical temperature and pressure. The curves generated by calculating around the **P-T** envelope tend to extrapolate to the point thought to represent the critical of the mixture. Based on these observations the critical temperature of a mixture can be defined as that temperature above which all of the mixture cannot be liquefied.

Another significant difference in mixture behavior is the existence of so-called retrograde regions in the two-phase envelope. This is better illustrated by Fig. 4. Consider a constant pressure heating path beginning at point 1 and extending to point 2. At point 1 the mixture would be a subcooled liquid. Heating to point A at that pressure would result in the mixture entering the two-phase region. Until a point approximately at B is reached, additional heating would cause additional liquid formation. From point B to point C there would be vaporization of the liquid that had been formed. At point 2 the mixture would be a single-phase dense gas. The same kind of thing would occur on a constant temperature-pressure decrease path beginning at point 3 and extending to point 4. This retrograde behavior has been observed for many years in hydrocarbon reservoirs at high temperatures and pressures. Recently, however, Maddox and Erbar [11] have shown that this retrograde behavior can be exhibited at pressures below 3.5 MPa and temperatures below 200 K.

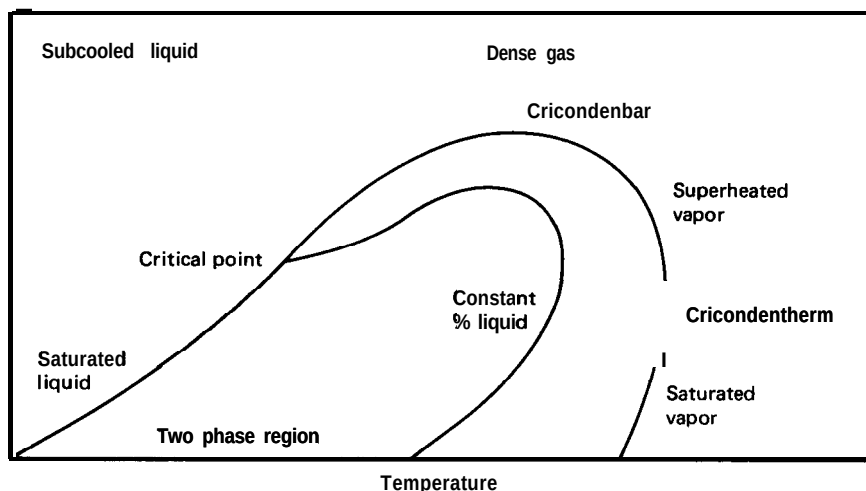


Figure 3 Phase envelope for a typical natural gas mixture.

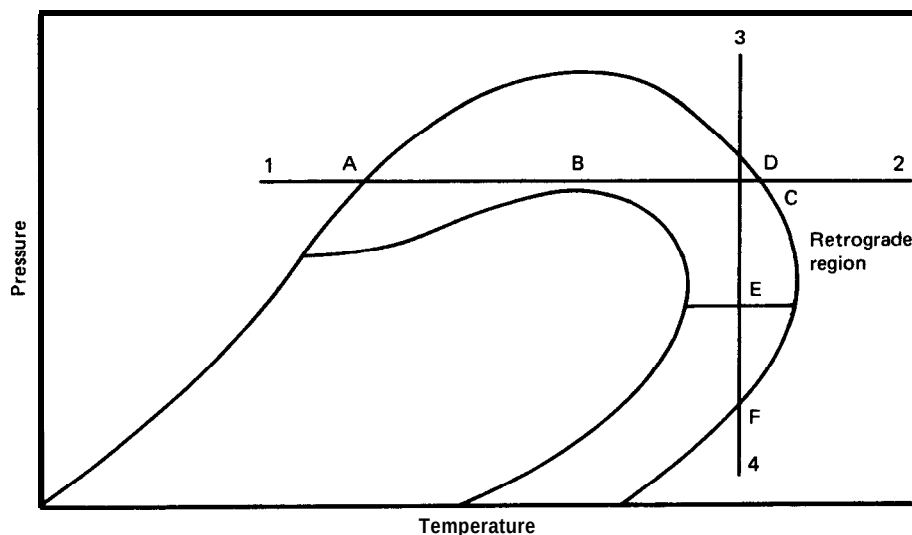


Figure 4 Retrograde behavior.

D. Nonhydrocarbon phase behavior

The vapor-liquid behavior of hydrocarbon mixtures has been investigated over a wider range of temperatures and pressures, particularly for the light hydrocarbon defined components, than most individual components in **non**-hydrocarbon mixtures. Hydrocarbons do illustrate some liquid-phase nonidealities. However, in most cases these are small when compared with the liquid-phase **non**-idealities that can exist in mixtures containing one or more nonhydrocarbons. Hydrocarbons, on the other hand, tend to be processed more frequently at pressures where pressure effects can cause serious shifts from ideal behavior. For these reasons, most attention in **nonhydro**-carbon mixtures tends to be directed to liquid-phase nonidealities.

Figure 5 shows a $\tilde{y}$ - $\tilde{x}$, or equilibrium, diagram for a binary mixture that exhibits ideal behavior. The curve may be used to replace traditional bubble point-dew point calculations using Henry's Law:

$$\tilde{y}_i = K_i \tilde{x}_i \quad (16)$$

If experimentally determined equilibrium constants for the mixture are not available, Raoult's law may be used in place of Henry's law:

$$\pi \tilde{y}_i = P_i^0 \tilde{x}_i \quad (17)$$

Nonideal vapor-liquid phase behavior is illustrated in Figs. 6 and 7. In Fig. 6 the nonideality is sufficient only to cause a point of inflection in the vapor-liquid equilibrium behavior. In Fig. 7 the $\tilde{y}$ - $\tilde{x}$ curve actually crosses the $\tilde{y}=\tilde{x}$ line. This represents an azeotrope or constant boiling mixture that, from a vapor-liquid equilibrium standpoint, behaves as a pure component. In

the **nonideal** system the K values, or equilibrium constants, may be expressed as

$$K = \gamma K^0 \quad (18)$$

Predicting the occurrence of the kind of behavior demonstrated in Figs. 6 or 7 is all but impossible. Experimental data on the particular system must be obtained and evaluated. Groupcontribution methods such as those discussed in Sec. 5.2.2 do show some promise for prediction in this area.

E. Phase behavior of mixtures of undefined components

Mixtures of undefined composition can occur in two ways: when they constitute the entire mixture, such as in crude oil fractions, or when they constitute only a portion of the total mixture, such as in most natural gases. In either case, some experimental data are necessary before the vapor-liquid phase behavior of the mixture can be satisfactorily predicted.

In most cases where a crude oil or a fraction of a crude oil constitutes the entire mixture, vapor-liquid equilibrium behavior is desired at low pressures. In this case the main problem becomes one of evaluating vaporization characteristics. Edmister[10] details a procedure including sample calculations for making these predictions. The integral technique treats the mixture of undefined components as a continuum (an excellent approximation for crude oil mixtures). It utilizes the density, boiling range, and true boiling point distillation to evaluate vaporization characteristics. It is applicable to flash vaporization, continuous and batch distillation.

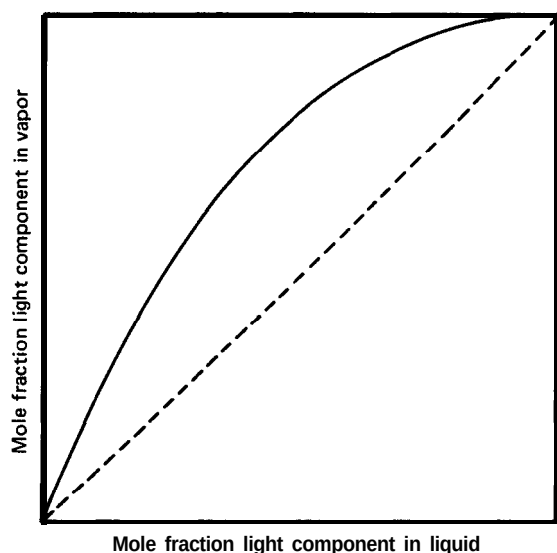


Figure 5 Equilibrium curve for ideal binary mixture.

For cases where the undefined component constitutes a small fraction of the total stream, and where an equation of state is to be used to predict vapor-liquid behavior, such as typical natural gas streams, more detailed procedures are required. Every equation of state capable of handling mixtures of undefined components requires as input to the computer program information concerning certain correlating parameters. These correlating parameters will include such characteristics as critical temperature, critical pressure, acentric factor, true boiling point curve, density, UOP characterization factor, etc. Wilson et al. [12] discuss the importance of characterizing undefined mixtures and describe a procedure for estimating the correlating parameters in such

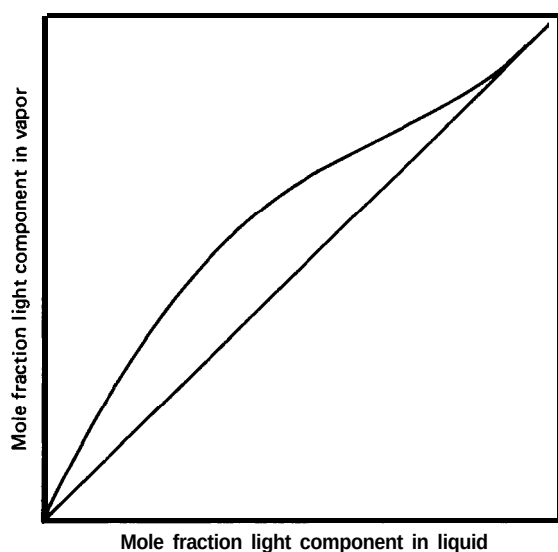


Figure 6 Equilibrium curve for nonideal binary mixture.

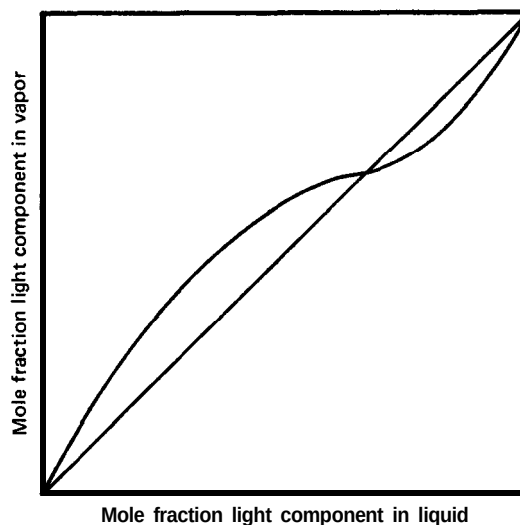


Figure 7 Equilibrium curve for a binary mixture with azeotrope.

a way as to match experimentally determined bubble point-dew point-percent vaporization data. Maddox and Erbar [13] provide discussion in greater detail along with example problems worked out in detail.

For a mixture of undefined composition, the most generally available information is the density (specific gravity) and the boiling range from either a simple or true boiling point distillation. From this information, other characteristics of the mixture can be predicted. Kesler and Lee [14] have presented equations that use density and boiling point to predict the following properties:

Critical temperature

$$T_c = 189.8 + 450.6SG + (0.4244 + 0.1174SG)T_b + (0.1441 - 1.0069SG)10^5/T_b \quad (19)$$

Critical pressure

$$\ln P_c = 17.2019 - \frac{0.0566}{SG} - \left(0.4364 + \frac{4.1216}{SG} + \frac{0.21343}{SG^2}\right)10^{-3}T_b + \left(4.7579 + \frac{11.819}{SG} + \frac{1.5302}{SG^2}\right)10^{-7}T_b^2 - \left(2.4505 + \frac{9.9009}{SG^2}\right) \times 10^{-10}T_b^3 \quad (20)$$

Acentric factor

$$\omega = -7.904 + 0.1352K - 0.007465K^2 + 8.359T_{br} + \frac{1.408 - 0.01063K}{T_{br}} \quad \text{for } T_{br} > 0.8 \quad (21)$$

Molecular weight

$$\begin{aligned}
 MW = & -12\,272.6 + 9\,486.4SG + (8.374\,1 \\
 & - 5.991\,2SG)T_b + (0.555\,56 - 0.428\,24SG \\
 & - 0.011\,433SG^2)\left(1.343\,7 - \frac{400.43}{T_b}\right)\frac{10^7}{T_b} \\
 & + (0.171\,5 - 0.138\,7SG + 0.003\,317SG^2) \\
 & \times \left(1.882\,8 - \frac{101.1}{T_b}\right)\frac{10^{12}}{T_b^3} \quad (22)
 \end{aligned}$$

where T_b = normal boiling point (taken as the mean of the boiling temperature range), K

SG = specific gravity (i.e., the ratio of the fluid density to the density of water at the same temperature, normally taken at 15.56°C)

T_{br} = reduced normal boiling point = T_b/T_c

K = Watson characterization factor = $1.216 (CABP)^{1/3}/SG$

CABP = cubic average boiling point (i.e., the cube root of the sum of the cubes of the maximum and minimum temperatures in the boiling range. Note that $CABP \approx T_b$ if the boiling range is small)

T_c = critical temperature, K

P_c = critical pressure, Pa

Equation (21) is intended for heavy mixtures having reduced normal boiling points greater than 0.8. For lighter mixtures, Eq. (23) should be used to predict the acentric factor.

$$\begin{aligned}
 w = & (\ln P_{br}^s - 5.927\,14 + \frac{6.069\,48}{T_{br}} + 1.288\,62 \ln T_{br} \\
 & - 0.169\,347 T_{br}^6)/(15.251\,8 - \frac{15.687\,5}{T_{br}} \\
 & - 13.472\,1 \ln T_{br} + 0.435\,77 T_{br}^6) \quad (23)
 \end{aligned}$$

where P_{br}^s = reduced vapor pressure at T_b .

Example

Calculate the properties of a 260°–315.6°C (533.15–588.75 K) boiling point range cut of a mid-continent crude oil which has a specific gravity of 0.842 3.

Solution

The first step in the solution is evaluation of the Watson characterization factor, K . This value is evaluated at the average of the boiling range, the mid-boiling point T_b (i.e., 560.95 K). The error introduced by this assumption will normally be small.

$$K = \frac{1.216 \sqrt[3]{560.95}}{0.842\,3} = 11.90 \quad (24)$$

The critical temperature can be evaluated from Eq. 19,

$$\begin{aligned}
 T_c = & 189.8 + 450.6(0.842\,3) + [0.424\,4 \\
 & + 0.117\,4(0.842\,3)] \times 560.95 + [0.144\,1
 \end{aligned}$$

$$- 1.006\,9(0.842\,3)] \frac{10^5}{T_b}$$

$$= 189.8 + 379.5 + 293.5 - 125.5 = 737.3\,K$$

$$T_{br} = \frac{560.95}{737.3} = 0.761$$

The critical pressure can be estimated by use of Eq. (20):

$$\begin{aligned}
 \ln P_c = & 1\,7\,2\,0\,1\,9 - E - \frac{0.436\,4 + \frac{4.121\,6}{SG}}{C} \\
 & + \frac{0.213\,43}{SG^2} \Big) 10^{-3} T_b + \left(4.757\,9 + \frac{11.819}{SG} \right. \\
 & \left. + \frac{1.530\,2}{SG^2} \right) 10^{-7} T_b^2 - \left(2.450\,5 + \frac{9.900\,9}{SG^2} \right) \\
 & \times 10^{-10} T_b^3 = 17.201\,9 - 0.067\,2 - 3.158\,4 \\
 & + 0.659\,1 - 0.289\,6
 \end{aligned}$$

$$\ln P_c = 14.345\,8$$

$$P_c = 1.699 \times 10^6 \text{ Pa}$$

$$P_{br} = \frac{1.013 \times 10^5}{1.699 \times 10^6} = 0.059\,62$$

Since the reduced boiling point is less than 0.8, Eq. (23) will be used to evaluate the acentric factor:

$$\begin{aligned}
 w = & \{\ln(0.059\,2) - 5.927\,141 + 6.069\,48/0.761 \\
 & + (1.288\,62 \ln 0.761) - [0.169\,347(0.761)^6]\}/ \\
 & \times [15.251\,8 - (15.687\,5/0.761) \\
 & - (13.472\,1 \ln 0.761) + 0.435\,79(0.761)^6] \\
 = & (-2.826\,83 - 5.927\,14 + 8.011\,4 - 0.351\,95 \\
 & - 0.032\,89)/(15.251\,8 - 20.614\,32 + 3.679\,53 \\
 & + 0.084\,64)
 \end{aligned}$$

$$\omega = \frac{-1.127\,41}{-1.598\,35} = 0.702\,3$$

The molecular weight for the fraction is

$$\begin{aligned}
 MW = & -12\,272.6 + 9\,486.4(0.842\,3) + [8.374\,1 \\
 & - 5.991\,2(0.842\,3)] (560.95) + [0.555\,56 \\
 & - 0.428\,24(0.842\,3) - 0.011\,433(0.842\,3)^2] \\
 & \times \left(1.343\,7 - \frac{400.43}{560.95} \right) \frac{10^7}{T_b} + [0.171\,5 \\
 & - 0.138\,7(0.842\,3) + 0.003\,817(0.842\,3)^2 \\
 & \times \left(1.882\,8 - \frac{101.1}{T_b} \right) \frac{10^{12}}{T_b^3} = -12\,272.6 \\
 & + 7\,990.4 + 1\,866.7 + 2\,096.9 + 553.3
 \end{aligned}$$

$$MW = 234.6$$

The true critical temperature of mixtures of natural gas rich in methane can be estimated through use of Fig. 8. (Figure 8 is taken after the chart in the API Technical Data Book-Refining [16]). The method requires estimation of the weight average API gravity. The API gravity is related to specific gravity by the formula: **API gravity = (141.5/SG) - 131.5**. For most components, values of density (and, hence, specific gravity) from Sec. 5.5.1 can be used. However, the following values must be used for the indicated components:

Component	Effective API gravity	Effective specific gravity
Methane	440	0.241
Ethane	213	0.410
Carbon dioxide	42	0.816
Nitrogen	43.6	0.808

Proper use of Fig. 8 is illustrated in the following example.

Estimate the true critical temperature of the natural gas consisting of methane (0.914 mole fraction), ethane (0.061 mole fraction), propane (0.011 mole fraction) and carbon dioxide (0.014 mole fraction).

Solution

1. Obtain the molecular weight for each component from Sec. 5.5.1 and calculate the mole fraction average molecular weight by summing the product of the mole fraction and molecular weight for each component:

Component	Mole fraction	Mole weight, kg/kmole	Mole fraction X molecular weight
Methane	0.914	16.042	14.66
Ethane	0.061	30.068	1.83
Propane	0.011	44.094	0.49
Carbon dioxide	0.014	44.011	0.62
Mole fraction average molecular weight			17.60

2. Calculate the weight fraction of each component by dividing the product of the mole fraction and the molecular weight for each component by the mole fraction average molecular weight (e.g., for methane, weight fraction = $14.66/17.60 = 0.833$).

3. Calculate the weight average API gravity.

Component	API gravity	Weight fraction	Weight fraction X API gravity
Methane	440	0.833	366.5
Ethane	213	0.104	22.2
Propane	147.2	0.028	4.1
Carbon dioxide	42.0	0.035	1.5
Weight fraction average API gravity = 394.3			

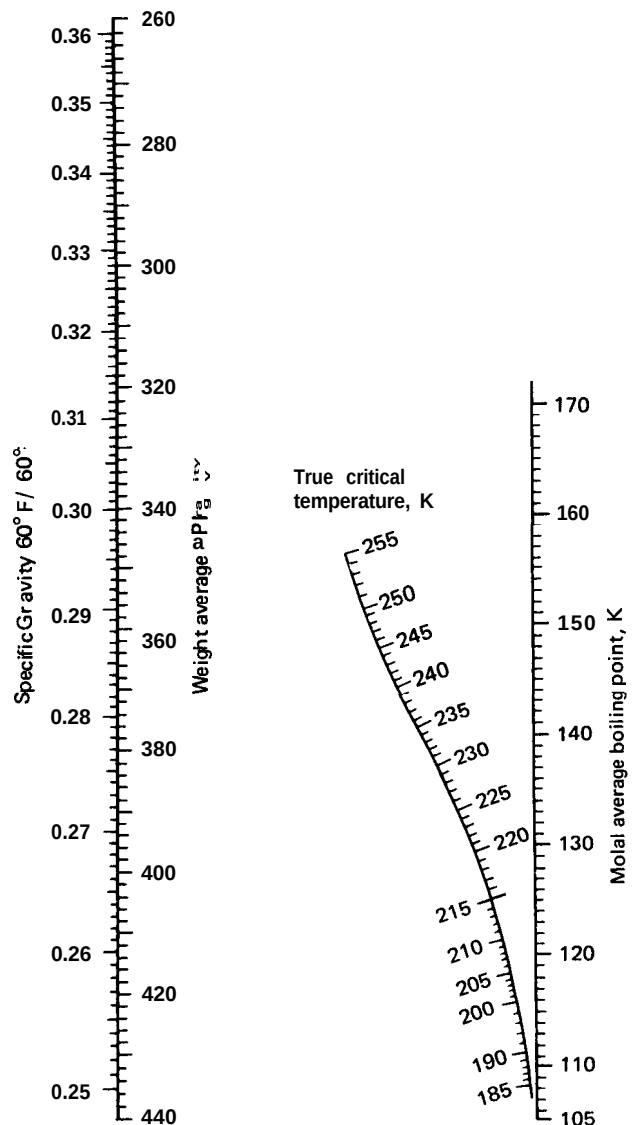


Figure 8 Critical temperature of natural gas mixtures.

4. Calculate the molal average boiling point.

Component	Boiling point, K	Boiling point X mole fraction
Methane	111.42	101.8
Ethane	184.52	11.3
Propane	231.1	2.5
Carbon dioxide	194.65	2.7
Mole fraction average boiling point = 118.3		

5. Read the mixture true critical temperature from Fig. 8. Draw a **line** between 394.3 on the left hand (weight, average API gravity) scale and 118.3 on the right hand (mole fraction average boiling point) scale and read off the critical temperature (206 K) from the curved scale.

References for Section 5.2. I appear at the end of Section 5.2.5.

5.2.2

Thermodynamics properties

R. N. Maddox

A. Light hydrocarbons

There are reasonably reliable charts available from which equilibrium constants for light hydrocarbons can be obtained. Perhaps the best, and most widely used, are those published by the Gas Processors Association [17]. Values from the charts, if properly used, will agree closely with the values obtained from a good equation of state. In addition, they are easily and quickly used and ideal for hand calculations.

If more accurate equilibrium constants are desired, or if equilibrium conditions are being predicted by computer, an equation of state is used for estimating the equilibrium constant values. The most widely used equations of state for light hydrocarbons are the Soave version of the Redlich-Kwong (SRK) [18-20], the Starling version of the Benedict-Webb-Rubin (BWR) [21], and the Peng-Robinson (PR) [22]. Each has advantages and disadvantages, proponents and opponents. More importantly, different computer solutions for each equation may yield equilibrium constants that are significantly different. Erbar and Maddox [23] have made comparison calculations for simple equilibrium flash calculations that differed by as much as 20%. The same equation of state was used for all calculations, the programming of the solution was different.

Equilibrium coefficients are calculated from the equation of state using one of the Eqs. 5.2.1(8)-5.2.1(11). All thermodynamic quantities may be related to each other by mathematical manipulation. The fugacity coefficient is related to pressure, volume, temperature, and compressibility factor by

$$\ln \gamma_{gi} = \frac{1}{\tilde{R}T} \int_v^\infty \left[\left(\frac{\alpha P}{\alpha n_i} \right)_{T, v, n_j} - \frac{\tilde{R}T}{V} \right] dV - \ln Z \quad (1)$$

where R is the universal gas constant, Z is the compressibility factor = PV/RT , and n_i is the number of moles of component i in the mixture.

To develop the equations for calculating the fugacity coefficient, the basic equation of state is differentiated and substituted into Eq. (1). A direct analytical solution for the fugacity coefficient results once the constants have been evaluated, if the volumetric behavior of the system is known.

Prediction of enthalpies and entropies is handled differently. Ideal gas values for these variables are known rather accurately. The calculation is broken into two steps: an isobaric influence of temperature and an isothermal influence of pressure. Mixture values for ideal gas behavior are taken as the composition weighted average.

The equations necessary for use in the SRK equation are shown in Table 1. The SRK is a two-constant, or two-parameter, equation. The constants A and B can be determined from the correlating parameters for each component in the mixture.

The equations for the Peng-Robinson equation are shown in Table 2. It also is a two-constant equation of state.

The BWR equations are shown in Table 3. They have eleven constants that must be evaluated for each component. More PVT data are required for determination of the eleven constants than would be required for the two-constant equations.

The k_{ij} terms that appear in the equations are the

Table 1 Equations for Soave-Redlich-Kwong equation of state

$$K_i = \frac{\phi_i^L}{\phi_i^V}$$

$$\ln \phi_i = \frac{b_i}{b} (Z - 1) - \ln (Z - B) - \frac{A}{B} \left[\frac{2(ac\alpha)_i}{ac\alpha} - \frac{b_i}{b} \right] \ln \left(1 + \frac{B}{Z} \right)$$

$$Z^3 - Z^2 + (A - B - B^2)Z - AB = 0.0$$

$$A = \frac{ac\alpha P}{R^2 T^2}; \quad B = b \frac{P}{T}; \quad b = \sum y_i b_i$$

$$b_i = \Omega_b \frac{RT_{ci}}{P_{ci}}; \quad a_{ci} = 0.42747 \frac{R^2 T_{ci}^2}{P_{ci}}$$

$$\Omega_b = 0.08667; \quad \alpha_{ci}^{0.5} = 1 + m_i(1 - T_{ri}^{0.5})$$

$$ac\alpha = \sum_i \sum_j x_i x_j a_{ci}^{0.5} a_{cj}^{0.5} \alpha_i^{0.5} \alpha_j^{0.5} (1 - k_{ij})$$

$$(ac\alpha)_i = \sum_{j=1}^n x_j a_{ci}^{0.5} a_{cj}^{0.5} \alpha_i^{0.5} \alpha_j^{0.5} (1 - k_{ij})$$

Table 2 Equations for Peng-Robinson equation of state

$$P = \frac{RT}{v - b} - \frac{a}{v(v + b) + b(v - b)}$$

$$Z^3 - (1 - B)Z^2 + (A - B^2 - 2B)Z - (AB - B^2 - B^3) = 0.0$$

$$\ln \phi_i = \frac{b_i}{b} (Z - 1) - \ln (Z - B) - \frac{A}{2\sqrt{2}B} \left(\frac{2 \sum_i x_i a_{ik}}{a} - \frac{b_i}{b} \right) \ln \left(\frac{Z + 2.414B}{Z - 0.414B} \right)$$

$$\frac{\Delta H}{RT} = Z - 1 + \frac{T da/dT - a}{2\sqrt{2}b} \ln \left(\frac{Z + 2.414B}{Z - 0.414B} \right)$$

$$a = \sum_i \sum_j x_i x_j (a_{ci} a_{cj} \alpha_i \alpha_j)^{1/2} (1 - k_{ij}) \quad A = \frac{aP}{R^2 T^2}$$

$$b = \sum x_i b_i \quad B = \frac{bP}{RT}$$

$$a_{ci} = 0.45124 \frac{R^2 T_{ci}^2}{P_{ci}}$$

$$b_i = 0.07780 \frac{RT_c}{P_c}$$

Table 3 Equations for Benedict-Webb-Rubin equation of state

$$\begin{aligned}
 p &= \rho RT + \left(B_0 RT - A_0 - \frac{C_0}{T^2} + \frac{D_0}{T^3} - \frac{E_0}{T^4} \right) \rho^2 + \left(bRT - a - \frac{d}{T} \right) \rho^3 + \alpha \left(a + \frac{d}{T} \right) \rho^6 + \frac{c\rho^3}{T^2} (1 + \gamma\rho^2) \exp(-\gamma\rho^2) \\
 B_0 &= \sum_i x_i B_{0i} \quad b = \sum_i \sum_j \sum_k x_i x_j x_k b_i^{1/3} b_j^{1/3} b_k^{1/3} \\
 A_0 &= \sum_i \sum_j x_i x_j A_{0i}^{1/2} A_{0j}^{1/2} (1 - k_{ij}) a = \sum_i \sum_j \sum_k x_i x_j x_k a_i^{1/3} a_j^{1/3} a_k^{1/3} \\
 C_0 &= \sum_i \sum_j x_i x_j C_{0i}^{1/2} C_{0j}^{1/2} (1 - k_{ij})^3 \alpha = \sum_i \sum_j \sum_k x_i x_j x_k \alpha_i^{1/3} \alpha_j^{1/3} \alpha_k^{1/3} \\
 \gamma &= \sum_i \sum_j x_i x_j \gamma_i^{1/2} \gamma_j^{1/2} \quad C = \sum_i \sum_j \sum_k x_i x_j x_k c_i^{1/3} c_j^{1/3} c_k^{1/3} \\
 D_0 &= \sum_i \sum_j x_i x_j D_{0i}^{1/2} D_{0j}^{1/2} (1 - k_{ij})^4 \quad d = \sum_i \sum_j \sum_k x_i x_j x_k d_i^{1/3} d_j^{1/3} d_k^{1/3} \\
 E_0 &= \sum_i \sum_j x_i x_j E_{0i}^{1/2} E_{0j}^{1/2} (1 - k_{ij})^5 \\
 H - H^0 &= \rho \left(B_0 RT - A_0 - \frac{4C_0}{T^2} + \frac{5D_0}{T^3} - \frac{6E_0}{T^4} \right) + \frac{1}{2} \rho^2 \left(2bRT - 3a - \frac{4d}{T} \right) \\
 &\quad + \frac{1}{5} \rho^5 \alpha \left(6a + \frac{7d}{T} \right) + \frac{c}{\gamma T^2} \left[3 - \left(3 + \frac{1}{2} \gamma \rho^2 - \gamma^2 \rho^4 \right) \exp(-\gamma\rho^2) \right] \\
 S - S^0 &= - \sum_i x_i R \ln(RT \rho x_i) - \rho \left(B_0 R + \frac{2C_0}{T^3} - \frac{3D_0}{T^4} + \frac{4E_0}{T^5} \right) - \frac{1}{2} \rho^2 \left(bR + \frac{d}{T^2} \right) + \frac{1}{5} \rho^5 \frac{\alpha d}{T^2} + \frac{2c}{\gamma T^3} \left[1 - \left(1 + \frac{1}{2} \gamma \rho^2 \right) \exp(-\gamma\rho^2) \right] \\
 RT \ln f_i &= RT \ln(\rho RT x_i) + \rho(B_0 + B_{0i})RT + 2\rho \sum_j x_j \left[- (A_0 A_{0i})^{1/2} (1 - k_{ij}) - \frac{(C_0 C_{0i})^{1/2}}{T^2} - (1 - k_{ij})^3 + \frac{(D_0 D_{0i})^{1/2}}{T^3} (1 - k_{ij})^4 \right. \\
 &\quad \left. - \frac{(E_0 E_{0i})^{1/2}}{T^4} (1 - k_{ij})^5 \right] - \frac{\rho^2}{2} \left[3(b^2 b_i)^{1/3} RT - 3(a^2 a_i)^{1/3} - \frac{3(d^2 d_i)^{1/3}}{T} \right] + \frac{\alpha \rho^5}{5} \left(3(a^2 a_i)^{1/3} + \frac{3(d^2 d_i)^{1/3}}{T} \right) \\
 &\quad + \frac{3\rho^5}{5} \left(a + \frac{d}{T} \right) (\alpha^2 \alpha_i)^{1/3} + \frac{3(c^2 c_i)^{1/3} \rho^2}{T^2} \left[\frac{1 - \exp(-\gamma\rho^2)}{\gamma\rho^2} - \frac{\exp(-\gamma\rho^2)}{2} \right] \\
 &\quad - \frac{2c}{\gamma T^2} \left(\frac{\gamma_i}{\gamma} \right)^{1/2} \left[1 - \exp(-\gamma\rho^2) \left(1 + \gamma\rho^2 + \frac{1}{2} \gamma^2 \rho^4 \right) \right]
 \end{aligned}$$

binary interaction parameters used to help force fit'' data on recalcitrant mixtures.

B. Nonhydrocarbons

Techniques used to predict vapor-liquid equilibrium behavior of nonhydrocarbons must be capable of describing a variety of nonideal behaviors. For this reason, they tend to be different from those used for the relatively well-behaved hydrocarbon systems. The currently used techniques for developing the activity coefficients needed for vapor-liquid equilibrium determinations for the mixtures involve the use of group contributions. In this

approach, the individual molecule is considered to be made up of specific functional groups. The behavior of the molecule can be estimated by summing the characteristics of the functional groups. There are three techniques for allocating the group characteristics, similar in principle but differing in detail. All three will be discussed. The analytical solution of groups (ASOG) procedure [21-24] was actually developed in two steps. The first step was to express the activity coefficient at infinite dilution (γ_{xi}^0) as

$$\ln \gamma_{xi}^0 = f(n_a, n_b) \quad (2)$$

where $n_a = n_b$ are the groups making up molecules in the binary mixture.

The second step in the development of ASOG, and

the currently most widely used, considers the activity coefficient to be made up of two contributions, one based on molecular size and one based on molecular interactions. The activity coefficient is calculated as the algebraic sum of these two contributions:

$$\log \gamma_{\ell i} = \log \gamma_{\ell i}^G + \log \gamma_{\ell i}^S \quad (3)$$

While this procedure sounds simple, the application is a little more complicated, involving the following steps:

1. Determine the number of size groups ($-\text{CH}_2-$, $-\text{CH}_3$, $-\text{CH}-$, $-\text{CO}-$, $-\text{OH}$) in the molecular structure for each component in the mixture.

2. The size term R_i is calculated from the number of size groups for each component and the composition of each component in the mixture:

$$R_i = \frac{S_i}{\sum_j S_j \tilde{x}_j} \quad (4)$$

where S_i is the number of size groups in molecule i , S_j is the number of size groups in molecule j , and $\tilde{x}_j$ is the mole fraction of component j in the mixture.

3. Calculate the size contribution to the activity coefficient for each component:

$$\log \gamma_{\ell i}^S = \log R_i - 0.434(1 - \log R_i) \quad (5)$$

4. From the composition of each pure component in the mixture and the number of each type of interaction group, calculate the composition of each interaction group in the mixture by

$$X_K = \frac{\sum_i \tilde{x}_i \nu_{Ki}}{\sum_K \sum_i \tilde{x}_i \nu_{Ki}} \quad (6)$$

where X_K is the composition of interaction group K , ν_K is the number of interaction groups of type K .

5. Obtain the interaction parameter A_K for each function group in the mixture. Some interaction parameters are tabulated in Sec. 5.5.4. If not listed there, the interaction parameters can be obtained by regression analysis of experimental data.

6. Calculate the group activity coefficients from

$$\ln \Gamma_K = -\ln \sum_{\ell} \chi_{\ell} A_{K\ell} + 1 - \sum_{\ell} \frac{\chi_{\ell} A_{K\ell}}{\sum_m \chi_m A_{\ell m}} \quad (7)$$

7. Calculate the standard state group activity coefficients (Γ_K^*) using Eq. (7) for a solution containing each component of the mixture. If a component has only one kind of interaction group, such as water or benzene, the standard state activity coefficient will be 1.0. Other components will have a standard state activity coefficient for each interaction group.

8. Calculate the group interaction to the activity coefficient by

$$\ln \gamma_{\ell i}^G = \sum_K \nu_{Ki} \ln \Gamma_K - \sum_K \nu_{Ki} \ln \Gamma_K^* \quad (8)$$

9. Calculate the activity coefficient from Eq. (3). The important point of the ASOG approach is that the group parameters depend on the group, not the arrangement of the group in the molecule.

Example

Using the ASOG procedure calculate the composition of the vapor in equilibrium with a 20-mole % solution of n-butanol in water. The temperature at which a solution of this concentration would boil is 92.25°C for 1-atm pressure.

Since the ASOG procedure considers the CH_3 and CH_2 groups to be equivalent, n-butanol contains four CH_2 groups and one OH group. In the ASOG procedure, water is treated as one size group but as 1.4 interaction groups.

For a 20-mole % solution of n-butanol in water, the size terms are (let 1 be n-butanol and 2 be water)

$$R_1 = \frac{5}{5 \times 0.2 + 0.8 \times 1} = 2.7778$$

$$R_2 = \frac{1}{1.8} = 0.5556$$

The size contributions to the activity coefficient can now be calculated:

$$\ln \gamma_1^S = 1 - 2.7778 + (2.7778) = -0.7561$$

$$\ln \gamma_2^S = 1 - 0.5556 + n(0.5556) = -0.1433$$

Calculate the mole fraction of each interaction group based on the specified 20-mole % n-butanol solution.

$$X_{\text{CH}_2} = \frac{4 \times 0.2}{4 \times 0.2 + 1 \times 0.2 + 0.8 \times 1.4} = 0.3774$$

$$X_{\text{OH}} = 0.6226$$

The interaction parameters can now be determined from Table 5.5.4(1).

$$A_{11} = 1, \quad A_{12} = 0.305$$

$$A_{21} = 0.0147, \quad A_{22} = 1.0$$

The group activity coefficients can now be calculated.

$$\begin{aligned} \ln \Gamma_1 &= -\ln (0.3774 + 0.6226 \times 0.305) \\ &\quad + \left(1 - \frac{0.3774}{0.3774 + 0.6226 \times 0.305} \right. \\ &\quad \left. - \frac{0.6226 \times 0.0147}{0.6226 + 0.3774 \times 0.0147} \right) \\ &= 0.5669 + 1 - 0.6653 - 0.0146 = 0.8870 \end{aligned}$$

$$\ln \Gamma_2 = -\ln \left(\frac{0.622 \ 6 + 0.377 \ 4 \times 0.014 \ 7}{1 - \frac{0.622 \ 6}{0.622 \ 6 + 0.377 \ 4 \times 0.014 \ 7} - \frac{0.377 \ 4 \times 0.305}{0.377 \ 4 + 0.622 \ 6 \times 0.305}} \right)$$

$$= 0.465 \ 0 + 1 - 0.991 \ 2 - 0.202 \ 9 = 0.270 \ 9$$

For pure n-butanol the group mole fractions are

$$X_{\text{CH}_2} = \frac{4 \times 1.0}{4 \times 1.0 + 1 \times 1.0} = 0.8$$

$$X_{\text{OH}} = 0.2$$

The standard state group activity coefficients in n-butanol are

$$\ln \Gamma_1^* = -\ln(0.8 + 0.2 \times 0.305) + \left(1 - \frac{0.8}{0.8 + 0.2 \times 0.305} - \frac{0.2 \times 0.014 \ 7}{0.2 + 0.8 \times 0.014 \ 7} \right)$$

$$= 0.149 \ 7 + 1 - 0.929 \ 2 - 0.013 \ 9 = 0.206 \ 6$$

$$\ln \Gamma_2^* = -\ln(0.2 + 0.8 \times 0.014 \ 7) + \left(1 - \frac{0.2}{0.2 + 0.8 \times 0.014 \ 7} - \frac{0.305}{0.8 + 0.2 \times 0.305} \right)$$

$$= 1.552 \ 3 + 1.0 - 0.944 \ 5 - 0.283 \ 4 = 1.324 \ 4$$

For pure water the mole fraction of CH_2 is 0 and the mole fraction of OH is 1.0. Using these concentrations the standard state activity coefficients are

$$\ln \Gamma_1^* = -\ln(0 + 1.0 \times 0.305) + \left(1 - 0 + \frac{1.0 \times 0.014 \ 7}{1 + 0} \right)$$

$$= 1.187 \ 4 + 1 - 0.014 \ 7 = 2.172 \ 7$$

$$\ln \Gamma_2^* = 0.0$$

The group interaction contribution to the activity coefficient is

$$\ln \Gamma_1^G = (4 \times 0.887 + 1 \times 0.270 \ 9) - (4 \times 0.206 \ 6 + 1 \times 1.324 \ 4)$$

$$= 3.818 \ 9 - 0.826 \ 4 - 1.324 \ 4 = 1.668 \ 1$$

$$\ln \Gamma_2^G = (0 \times 0.887 + 1.4 \times 0.270 \ 9) - (0 \times 2.172 \ 7 + 1.4 \times 0.379 \ 3)$$

The activity coefficients for n-butanol and water in 20-mole % solution are

$$\gamma_1 = \exp(1.668 \ 1 - 0.756 \ 1) = 2.489 \ 3$$

$$\gamma_2 = \exp(0.379 \ 3 - 0.143 \ 3) = 1.266 \ 3$$

The activity coefficient may be related to vapor and liquid composition by

$$\gamma = \frac{yP}{xP^0}$$

Palmer [27] gives equations for the vapor pressure of n-butanol and water:

$$n\text{C}_4\text{OH} \log P^0 = 9.067 \ 429 - \frac{2 \ 295.061 \ 1}{254.29 + t}$$

$$\text{H}_2\text{O} \log P^0 = 7.966 \ 81 - \frac{1 \ 668.21}{228.0 + t}$$

Perry et al. [30] give the constant boiling azeotropic temperature for n-butanol and water as 92.25°C . At this temperature the vapor composition in equilibrium with the 20% liquid solution would be

$$2.489 \ 3 + \frac{y_1}{0.2 \times 278.38} \quad y_1 = 0.192 \ 9$$

$$1.266 \ 3 = 0.8 \times \frac{y_2}{572.43} \quad y_2 = 0.807 \ 1$$

The calculated vapor composition is very nearly the same as the liquid composition. This actually represents a region of partial immiscibility for the n-butanol-water system. In detailed calculations using ASOG [27], Palmer indicates that the group contribution approach does very well in predicting this vapor composition and region of partial miscibility.

Cunningham [28] presented the essentials of the parameters from the group contribution (PFGC) procedure, and the equation of state is

$$Z = \frac{PV}{nRT} = 1 - \frac{sV}{nb} \ln \frac{V - nb}{V} - S + b \frac{C}{b_H} \sum_i \Psi_i \frac{nb - b}{V - nb} + \sum_j \frac{\Psi_j \lambda_{ij}}{nb \sum_i \Psi_i \lambda_{ij}} \quad (9)$$

where

$$S = \sum_I S_I \tilde{x}_I \quad S_I = \sum_i m_{Ii} S_i v_i$$

n = number of moles

b = volume of occupied lattice sites

V = volume

C_{bH} = universal constant = 12.0

Ψ = group fraction

λ = group interaction term

i = group property

j = group property

I = molecular property and equals the number of lattice sites per group

The third group contribution method to be considered is UNIFAC developed by Prausnitz and co-workers [29]. It has the advantage that mixture properties can be estimated from pure-component measurements without need for mixture data. In fashion similar to ASOG, the activity coefficient is considered to be composed of two parts: one due to differences in size and shape of the molecules in the mixture (the combinatorial portion) and one due to energy interactions (the residual portion).

$$\ln \gamma_i = \ln \gamma_i^C + \ln \gamma_i^R \quad (10)$$

where R stands for residual and C for combinatorial.

The combinatorial portion of the activity coefficient is calculated directly from the values tabulated in Sec. 5.5.4 using the relationship

$$\ln \gamma_i^C = \ln \frac{\Phi_i}{\tilde{x}_i} + \frac{z}{2} q_i \ln \frac{\Theta_i}{\Phi_i} + \ell_i - \frac{\Phi_i}{\tilde{x}_i} \sum_j \tilde{x}_j l_j \quad (11)$$

where $\ell_i = z/2(r_i - q_i) - (r_i - 1)$, $r_i = \sum_K \nu_K^{(i)} R_K$ is a measure of molecular van der Waals volume, $z = 10$, $\nu_K^{(i)}$ = number of K groups in molecule i , R_K, Q_K are values tabulated in Sec. 5.5.4, Θ_i is the area fraction = $q_i \tilde{x}_i / \sum_j q_j \tilde{x}_j$, $q_i = \sum_K \nu_K^{(i)} Q_K$ is a measure of molecular surface area, $\Phi_i = V \tilde{x}_i / \sum_j r_j \tilde{x}_j$ is the segment fraction, similar to volume fraction.

The residual portion of the activity coefficient is calculated by

$$\ln \gamma_i^R = \sum_K \nu_K^{(i)} (\ln \Gamma_K - \ln \Gamma_K^{(i)}) \quad (12)$$

where Γ_K is the group residual activity coefficient and $\Gamma_K^{(i)}$ the residual activity coefficient of group K in a solution containing only molecule i .

The group activity coefficients in Eq. (12) are calculated from

$$\ln \Gamma_K = Q_K \left[1 - \ln \left(\sum_m \Theta_m \Psi_{mK} \right) - \sum_m \frac{\Theta_m \Psi_{mK}}{\sum_n \Theta_n \Psi_{nm}} \right] \quad (13)$$

where $\Theta_m = Q_m X_m / \sum_n Q_n X_n$ is the fraction of group m , X_m is the mole fraction of group m in the mixture, $\Psi_m = \exp(-a_{mn}/T)$ is the group interaction parameter, and a_{mn} is the group interaction parameter tabulated in Sec. 5.4.4. Note $a_{mn} \neq a_{nm}$.

The chronological steps in solution of the UNIFAC equations are as follows:

1. Using Table 5.5.4(2) identify the kind and number of groups in each molecule in the solution.
2. Calculate the parameters for molecular volume and molecular surface area from

$$r_i = \sum_K \nu_K^{(i)} R_K$$

$$q_i = \sum_K \nu_K^{(i)} Q_K$$

3. Calculate the parameter ℓ_i from

$$\ell_i = \frac{z}{2} (r_i - q_i) - (r_i - 1.0)$$

4. Calculate the segment fractions and area fractions based on the specified composition

$$\Theta_i = \frac{q_i \tilde{x}_i}{\sum_j q_j \tilde{x}_j}$$

$$\Phi_i = \frac{r_i \tilde{x}_i}{\sum_j r_j \tilde{x}_j}$$

5. Calculate the combinatorial portion of the activity coefficient from Eq. (11).

6. For the pure components calculate the area fractions and group interaction parameters from Table 5.5.4(3). (Note that Θ_m is not the same as Θ_i that is used in calculating the combinatorial portion of the activity coefficient.)

$$\Theta_m = \frac{Q_m X_m}{\sum_n Q_n X_n}$$

$$\Psi_m = \exp \frac{-a_{mn}}{T}$$

7. Calculate the pure component residual activity coefficients from Eq. (13).

8. Repeat steps 6 and 7 for the specified solution concentration.

9. Calculate the residual portion of the activity coefficient using Eq. (12).

10. Calculate the activity coefficient for each component in the mixture using Eq. (10).

Example

Calculate the activity coefficients for the 20% n-butanol in water solution for the same conditions as used in the ASOG example.

From Table 5.5.4(2) the groups in the mixture are:

n-Butanol: 1 CH_3 ; 2 CH_2 ; 1 COH

Water: 1 H_2O

The volume and surface area parameters for these groups are:

Group	R_K	Q_K
CH_3	0.9011	0.848
CH_2	0.6744	0.540
COH	1.2044	1.124
H_2O	0.92	1.400

Denoting n-butanol as component 1 in the mixture and water as component 2, the parameters for molecular volume and molecular surface area may be calculated:

$$r_1 = 0.901 \cdot 1 + 2 \cdot 0.674 \cdot 4 + 1.204 \cdot 4 = 3.454 \cdot 3$$

$$r_2 = 0.920 \cdot 0$$

$$q_1 = 0.848 + 2 \cdot 0.540 + 1.124 = 3.055$$

$$q_2 = 1.40$$

The area fractions and volume fractions can now be calculated as can the parameter Q

$$\Theta_1 = \frac{3.052 \cdot \frac{3}{3.454} \cdot 0.2}{3.052 \cdot \frac{3}{3.454} \cdot 0.2 + 1.4 \cdot 0.8} = 0.352 \cdot 8$$

$$\Theta_2 = 0.647 \cdot 2$$

$$\Phi_1 = \frac{3.454 \cdot \frac{3}{3.454} \cdot 0.2}{3.454 \cdot \frac{3}{3.454} \cdot 0.2 + 0.92 \cdot 0.8} = 0.484 \cdot 2$$

$$\Phi_2 = 0.515 \cdot 8$$

$$I_1 = 5(3.454 \cdot 3 - 3.052) - (3.454 \cdot 3 - 1.0) = -0.442 \cdot 8$$

$$I_2 = 5(0.92 - 1.4) - (0.92 - 1.0) = -2.32$$

The combinatorial portion of the activity coefficient can now be calculated from Eq. (11).

$$\begin{aligned} \ln \gamma_1^C &= \ln \left(\frac{0.484 \cdot 2}{0.2} \right) + \left(5 \times 3.052 \ln \frac{0.352 \cdot 8}{0.484 \cdot 20} \right) \\ &\quad - 0.442 \cdot 8 - \frac{0.3528/0.2}{0.2(-0.442 \cdot 8) + 0.8(2.32)} \\ &= -0.959 \cdot 7 \end{aligned}$$

$$\begin{aligned} \ln \gamma_2^C &= \ln \left(\frac{0.515 \cdot 8}{0.8} \right) + \left[5 \times 1.4 \ln \left(\frac{0.647 \cdot 2}{0.515 \cdot 8} \right) \right] \\ &\quad - 2.32 - \frac{0.515 \cdot 8/0.8}{0.2(-0.442 \cdot 8) + 0.8(2.32)} \\ &= 0.083 \cdot 5 \end{aligned}$$

The next step in the calculation is to determine the residual portion of the activity coefficient through use of Eqs. (12) and (13). The first step is to determine the residual activity coefficient for a solution containing only n-butanol and then only water. In this portion of the calculation subscript 1 will refer to CH_3 , subscript 2 to CH_2 , subscript 3 to COH , and subscript 4 to water. For pure n-butanol the area fractions for use in Eq. (13) are

$$\Theta_1 = \frac{0.848 + 2(0.540) + 1.124}{0.848 + 2(0.540) + 1.124} = 0.277 \cdot 9$$

$$\Theta_2 = 0.353 \cdot 9$$

$$\Theta_3 = 0.368 \cdot 3$$

Group interaction parameters may be determined from Table 5.5.4(3). Using these values and the temperature of 92.25°C reported for the azeotrope, the group interaction coefficients are

$$\Psi_{11} = \Psi_{22} = \Psi_{33} = \Psi_{12} = \Psi_{21} = 1.0$$

$$\Psi_{23} = \Psi_{13} = \exp \left(-\frac{931.2}{365.4} \right) = 0.078 \cdot 2$$

$$\Psi_{32} = \Psi_{31} = \exp \left(-\frac{169.7}{365.4} \right) = 0.628 \cdot 5$$

$$\Psi_{24} = \Psi_{14} = \exp \left(-\frac{145.2}{365.4} \right) = 0.018 \cdot 8$$

$$\Psi_{41} = \Psi_{42} = \exp \left(-\frac{657.7}{365.4} \right) = 0.165 \cdot 3$$

$$\Psi_{34} = \exp \left(-\frac{320.8}{365.4} \right) = 2.405 \cdot 9$$

$$\Psi_{43} = \exp \left(-\frac{287.5}{365.4} \right) = 0.455 \cdot 3$$

Both the pure component activity coefficient and the activity coefficients in solution are calculated using Eq. (13). For the three groups in n-butanol (CH_3 , CH_2 , COH) the expanded form of Eq. (13) is

$$\begin{aligned} \ln \Gamma_1^{(1)} &= Q_1 \left[1 - \ln (\Theta_1 \Psi_{11} + \Theta_2 \Psi_{21} + \Theta_3 \Psi_{31}) \right. \\ &\quad - \frac{\Theta_1 \Psi_{11}}{\Theta_1 \Psi_{11} + \Theta_2 \Psi_{21} + \Theta_3 \Psi_{31}} \\ &\quad - \frac{\Theta_2 \Psi_{12}}{\Theta_1 \Psi_{12} + \Theta_2 \Psi_{22} + \Theta_3 \Psi_{32}} \\ &\quad \left. - \frac{\Theta_3 \Psi_{13}}{\Theta_1 \Psi_{13} + \Theta_2 \Psi_{23} + \Theta_3 \Psi_{33}} \right] \end{aligned}$$

$$\begin{aligned} \ln \Gamma_2^{(1)} &= Q_2 \left[1 - \ln (\Theta_1 \Psi_{12} + \Theta_2 \Psi_{22} + \Theta_3 \Psi_{32}) \right. \\ &\quad - \frac{\Theta_1 \Psi_{21}}{\Theta_1 \Psi_{11} + \Theta_2 \Psi_{21} + \Theta_3 \Psi_{31}} \\ &\quad - \frac{\Theta_2 \Psi_{22}}{\Theta_1 \Psi_{12} + \Theta_2 \Psi_{22} + \Theta_3 \Psi_{32}} \\ &\quad \left. - \frac{\Theta_3 \Psi_{23}}{\Theta_1 \Psi_{13} + \Theta_2 \Psi_{23} + \Theta_3 \Psi_{33}} \right] \end{aligned}$$

$$\begin{aligned} \ln \Gamma_3^{(1)} &= Q_3 \left[1 - \ln (\Theta_1 \Psi_{13} + \Theta_2 \Psi_{23} + \Theta_3 \Psi_{33}) \right. \\ &\quad - \frac{\Theta_1 \Psi_{31}}{\Theta_1 \Psi_{11} + \Theta_2 \Psi_{21} + \Theta_3 \Psi_{31}} \\ &\quad - \frac{\Theta_2 \Psi_{32}}{\Theta_1 \Psi_{12} + \Theta_2 \Psi_{22} + \Theta_3 \Psi_{32}} \\ &\quad \left. - \frac{\Theta_3 \Psi_{33}}{\Theta_1 \Psi_{13} + \Theta_2 \Psi_{23} + \Theta_3 \Psi_{33}} \right] \end{aligned}$$

Using these equations and the area fractions and interaction parameters calculated earlier, the pure component activity coefficients for n-butanol can be calculated as follows:

$$\ln \Gamma_1^{(1)} = 0.848 \left[1 - \ln (0.2779 \times 1 + 0.3539 \times 1 + 0.3683 \times 0.6285) \right. \\ \left. - \frac{0.2779 \times 1}{0.2779 \times 1 + 0.3539 \times 1 + 0.3683 \times 0.6285} \right. \\ \left. - \frac{0.3539 \times 1}{0.2779 \times 1 + 0.3539 \times 1 + 0.3683 \times 0.6285} \right. \\ \left. - \frac{0.3683 \times 0.0782}{0.2779 \times 0.0782 + 0.3539 \times 0.0782 + 0.3683 \times 1} \right] \\ = 0.2936 \\ \ln \Gamma_2^{(1)} = 0.540 \left[1 - 0.1869 \right. \\ \left. - \frac{0.2779 \times 0.6285}{0.2779 \times 1 + 0.3539 \times 1 + 0.3683 \times 0.6285} \right. \\ \left. - \frac{0.3529 \times 0.6285}{0.2779 \times 1 + 0.3539 \times 1 + 0.3683 \times 0.6285} \right. \\ \left. - \frac{0.3683 \times 1}{0.2779 \times 1 + 0.3539 \times 1 + 0.3683 \times 0.6285} \right] \\ = 0.5972$$

For pure water, $\ln \Gamma_4^{(1)} = 0.0$.

The residual portion of the activity coefficient must now be calculated for a 20% solution of n-butanol in water. For this solution the group mole fractions in the mixture are

$$X_1 = \frac{0.2 \times 1}{0.2 \times 4 + 0.8 \times 1} = 0.125$$

$$X_2 = 0.25 \quad X_3 = 0.125 \quad X_4 = 0.50$$

Based on these mole fractions the area fraction for each group can be calculated:

$$\Theta_1 = \frac{0.125 \times 0.848}{0.125 \times 0.848 + 0.25 \times 0.54 + 0.125 \times 1.124 + 0.5 \times 1.4} = 0.098$$

$$\Theta_2 = 0.1248$$

$$\Theta_3 = 0.1299$$

$$\Theta_4 = 0.6472$$

Earlier in the solution, Eq. (13) was expanded for the three groups occurring in n-butanol. This expansion shows a number of terms that recur in the calculations for each activity coefficient. For this reason these

terms will be evaluated separately and utilized in the activity coefficient calculations which follow them.

$$\Theta_1 \Psi_{11} + \Theta_2 \Psi_{21} + \Theta_3 \Psi_{31} + \Theta_4 \Psi_{41} = 0.098 \times 1 \\ + 0.1248 \times 1 + 0.1299 \times 0.6285 \\ + 0.6472 \times 0.1653 = 0.4114$$

$$\Theta_1 \Psi_{12} + \Theta_2 \Psi_{22} + \Theta_3 \Psi_{32} + \Theta_4 \Psi_{42} = 0.098 \\ \times 0.0782 + 0.1248 \times 1 + 0.1299 \times 0.6285 \\ + 0.6472 \times 0.1653 = 0.4114$$

$$\Theta_1 \Psi_{13} + \Theta_2 \Psi_{23} + \Theta_3 \Psi_{33} + \Theta_4 \Psi_{43} = 0.098 \\ \times 0.0782 + 0.1248 \times 0.0782 + 0.1299 \times 1 \\ + 0.6472 \times 0.4553 = 0.442$$

$$\Theta_1 \Psi_{14} + \Theta_2 \Psi_{24} + \Theta_3 \Psi_{34} + \Theta_4 \Psi_{44} = 0.098 \\ \times 0.0188 + 0.1248 \times 0.0188 + 0.1299 \\ \times 2.4059 + 0.6472 \times 1 = 0.9639$$

$$\ln \Gamma_1 = 0.848 \left(1 - \ln 0.4114 - \frac{0.098}{0.4114} \right. \\ \left. - \frac{0.1248}{0.4114} - \frac{0.1299 \times 0.0782}{0.442} \right) = 1.1117$$

$$\ln \Gamma_2 = 0.7079$$

$$\ln \Gamma_3 = 0.4869$$

$$\ln \Gamma_4 = 0.1989$$

The residual portion of the activity coefficient is calculated for each component by Eq. (12):

$$\ln \gamma_1^R = 1(1.1117 - 0.2936) + 2(0.7079 - 0.1869) \\ + 1(0.4869 - 0.5973) = 1.7498$$

$$\ln \gamma_2^R = 0.1989$$

The activity coefficients for n-butanol and water in a 20% solution of n-butanol in water are calculated from Eq. (10):

$$\ln \gamma_1 = 1.7498 - 0.9597 = 0.7901 \quad \gamma_1 = 2.2036$$

$$\ln \gamma_2 = 0.1981 + 0.835 = 1.0331 \quad \gamma_2 = 2.800$$

From the ASOG example we know that $P_{H_2O}^0 = 572.43$ and $P_{nC_4OH}^0 = 278.38$. If we assume that there is ideal behavior in the vapor phase, the composition of the vapor phase is

$$\pi \tilde{y}_i = \gamma_i \tilde{x}_i P_i^0 = 2.2036 \times 0.2 \times 278.38 \\ = 122.7 \text{ mm Hg}$$

$$y_1 = 0.168$$

$$\pi \tilde{y}_2 = \gamma_2 \tilde{x}_2 P_2^0 = 1.325 \times 0.8 \times 572.43$$

$$= 606.9 \text{ mm Hg}$$

$$y_2 = 0.832$$

The agreement here is not quite as good as with the ASOG procedure. However, the ASOG constants contain more fitting for specific behavior. For a

generalized predictive procedure the UNIFAC procedure seems to **give** excellent results.

Although cumbersome for hand calculations, the group contribution procedures are readily **program-**mable for digital computer solutions. If extensive use is to be made of any of them, computer solution is recommended.

Nomenclature for Section 5.2.2 appears at the beginning of Part 5. References appear at the end of Section 5.2.5.

5.2.3

Thermophysical properties

R. N. Maddox

■ Estimating the properties of mixtures requires, in general, knowledge of the properties of the pure components of which the mixture is comprised. The effort is to combine these pure component properties in such a way as to yield the properties of the mixture. In many instances, mixture properties are well behaved, and reasonably accurate prediction of properties is easily accomplished. There are cases, however, in which mixture properties behave badly and prediction is difficult. There are mixtures of relatively common materials for which properties go through a maximum or minimum that cannot be predicted a priori, and that are impossible to predict from pure component properties. As a simple example [30] consider that the density of a mixture of acetic acid and water goes through a maximum with composition. The author's experience indicates that this behavior will be at all temperatures to the mixture critical, although the composition at which the maximum/minimum exists may shift with changes in temperature.

The methods discussed below will deal with the problem of predicting mixture properties from those of the pure components. However, when methods are available, attention will also be given to techniques for predicting mixture properties directly.

A. Liquid density

Mixture density predictions are usually based on weighted averages from composition. The correct procedure requires only that attention be given to keeping dimensional consistency in the calculations. If

pure component densities are available on a mass/volume basis, the correct procedure is

$$\rho_{\text{mix}} = \sum v_i \rho_i \quad (1)$$

If, on the other hand, pure component values are available for molar volumes, then

$$\rho_{\text{mix}} = \sum \tilde{x}_i \rho_i \quad (2)$$

The dimensional consistency of each is clear. For Eq. (1):

$$\left(\frac{\text{kg}}{\text{m}^3} \right)_{\text{mix}} = \sum \frac{v_i}{V_{\text{mix}}} \frac{\text{kg}_i}{v_i}$$

For Eq. (2):

$$\left(\frac{\text{N}}{\text{m}^3} \right)_{\text{mix}} = \sum \frac{V_i}{V_{\text{mix}}} \frac{N_i}{\text{m}^3}$$

where v = volume fraction of one component in mixture

V = volume of one component

i = any component

mix = mixture

The **Rackett** equation [31] can be used for mixture density. It does require a limited amount of mixture density data for application. In this use it is written as

$$\rho = AB^{-(1-T/C)^{2/7}} \quad (3)$$

where A , B , and C are constants. If sufficient data are available to obtain reliable values for the constants by nonlinear regression, Eq. (3) can be used to extend

density data over a wide temperature range. The constants are composition specific and can be used for only one mixture composition.

There are no a priori ways to estimate the density of hydrocarbon mixtures of undefined composition. Generally, the density at ambient conditions and the boiling range of the fraction are known. Figure 1 [32] can be used to determine the density of the undefined mixture at other temperatures.

Unless data are collected in the critical region, density is influenced very little by pressure change. For this reason process engineering requirements will normally be satisfied by taking into account temperature changes while neglecting pressure changes.

B. Viscosity

There are no reliable techniques for estimating mixture viscosity in the absence of experimental data. If the system is well behaved and the mixture viscosity varies monotonically between the viscosities of the pure components, a mole fraction or mass fraction average will generally come within 15% of the mixture viscosity. The great danger, however, is that the mixture will exhibit either a maximum or a minimum. If this happens, the values estimated by averaging may be in error by a substantial margin. The simple acetone-water binary mixture displays a viscosity maximum with composition in which the mixture viscosity is

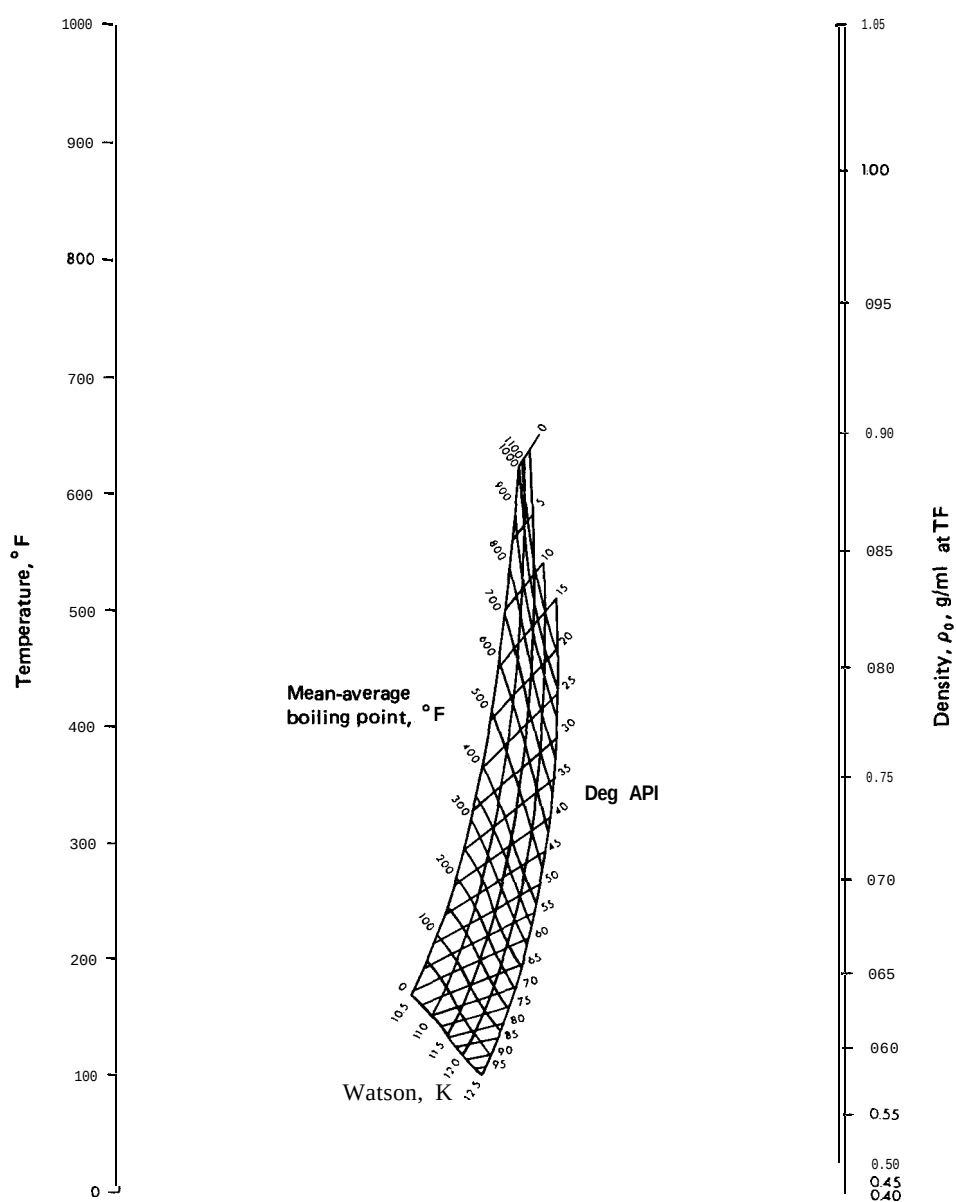


Figure 1 Density for mixtures of undefined components

more than 100% higher than that for either pure component. Simple mass fraction averaging obviously cannot be used on such a system. Unfortunately, there is no way to predict such behavior except for experimental measurements.

Reid and Sherwood [33] suggest for binaries the use of a modification of the procedure suggested for pure components by Souders [31]:

$$\log (\log 10 \eta_{Lm}) = \rho_{Lm} \left(\frac{\tilde{x}_1 T_1 \tilde{x}_2 T_2}{\tilde{x}_1 M_1 + \tilde{x}_2 M} \right) - 2.9 \quad (4)$$

where η_{Lm} = mixture viscosity, cP

$\tilde{x}$ = mole fraction

I = viscosity constant calculated from Table 1 [34]

ρ_{Lm} = mixture density in g mole/cm³

M = molecular weight

Equation (4) can be used to predict the viscosity of binary mixtures in the absence of either pure component or mixture data. If there is no maximum or minimum in the viscosity-composition curve, errors should be in the 20-25% range for mixtures of hydrocarbons and nonpolar, nonassociating materials; mixtures of polar and/or associating components will display larger errors, and may be completely unreliable.

If a limited amount of experimental data for the

mixture is available, it may be extrapolated to higher or lower temperature by plotting log viscosity as a function of reciprocal temperature. This technique must be used with caution because the log $\eta - 1/T$ relationship is truly linear only for a very few pure materials, and even fewer mixtures.

For mixtures of undefined composition, minimal information is necessary before the viscosity can be estimated. If the density and true boiling point for the fraction are known, the procedure recommended by the American Petroleum Institute [35] can be used. In this procedure, Fig. 2 is used to estimate the kinematic viscosity at temperatures of 100 and 200° F. These kinematic viscosities are then plotted on graph paper (very nearly log ν versus $1/T$) to obtain viscosities at other temperatures.

Amin and Maddox [36-39] made an extensive study of viscosity-temperature behavior for crude oil fractions. They concluded that oil mixtures followed the log $\nu - 1/T$ linear relationship, but that other materials, even pure components, did not. By regression analysis of data from the literature and other sources, Amin and Maddox developed an equation relating kinematic viscosity for crude oil fractions to easily measured and generally readily available information. Their equation is

Table 1 Values for determining viscosity constant in Eq. (4)

Group values					
CH ₂	55.6	OH	57.1	N	37
H	2.7	c o o	90	Cl	60
C	50.2	COOH	104.4	Br	79
O	29.7	NO ₂	80	I	110
Structural values ^a					
Double bond	- 15.5	$\begin{array}{c} \text{R} \quad \text{R} \\ \diagdown \quad \diagup \\ \text{CHCH} \\ \diagup \quad \diagdown \\ \text{R} \quad \text{R} \end{array}$	+ 8	-CH=CHCH ₂ X +	4
5-C ring	- 24				
6-C ring	- 21				
Side group on 6-C ring: Molecular weight less than 17	- 9	$\begin{array}{c} \text{R} \\ \\ \text{R}-\text{C}-\text{R} \\ \\ \text{R} \end{array}$	+ 13	$\begin{array}{c} \text{R} \\ \\ \text{CHX} \\ \\ \text{R} \end{array}$	+ 6
Molecular weight more than 16	- 17	$\begin{array}{c} \text{H}-\text{C}-\text{R} \\ \\ \text{O} \end{array}$	+ 10		
Ortho and para	+ 3				
Meta	+ 1	$\text{CH}_2-\text{C}-\text{R} \\ \\ \text{O}$	+ 5		

^aX is a negative group.

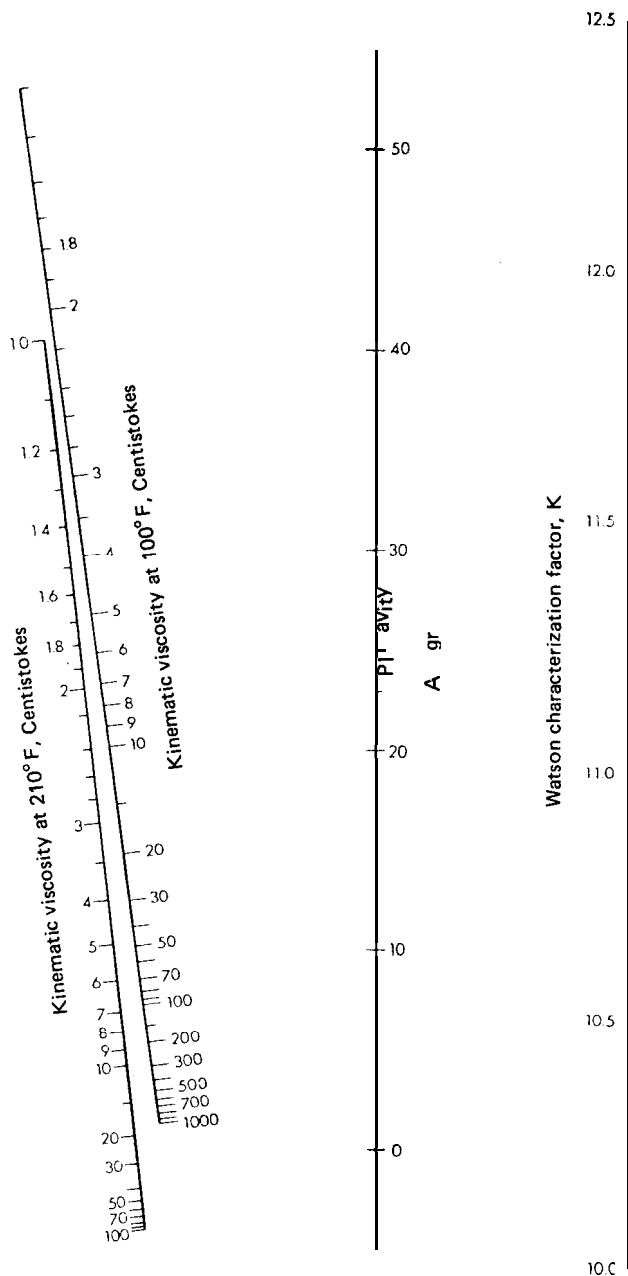


Figure 2 Viscosity for mixtures of undefined components.

$$\nu = A_{\text{exp}} \frac{B}{T} \quad (5)$$

where ν = kinematic viscosity in centistokes

A = constant $= (223 T_b^{-0.568} - 4.038) K/B$

B = constant $\ln B = 4.924 + 0.00454 T_b$

T_b = 50% boiling point in K

T = temperature, K

Example

Estimate the viscosity of a 200°-500°F boiling range cut of a crude oil at a temperature of 93.4°C. The cut is from a typical mid-continent U.S. crude oil,

has a 50% boiling point of 415.22 K, and a UOPK of 11.95 [38].

Equation (5) will be used to estimate the viscosity of the crude. The constants A and B in the equation are evaluated as:

$$B = \exp(4.924 + 0.00454 \times 415.22) = 906.05$$

$$A = (223 \times 415.22^{-0.568} - 4.038) \left(\frac{11.95}{906.05} \right) = 0.0425$$

Using these constants in Eq. (5) the kinematic viscosity of the crude oil is estimated as

$$\nu = 0.0425 \exp \frac{906.05}{934 + 27315} = 0.5033 \text{ cs}$$

The value of kinematic viscosity based upon experimental measurements of the absolute viscosity and density is 0.4813 cS [38].

If the viscosity of the fraction were desired at 10 000 psia, Fig. 3 would be employed. The experimentally determined density for the fraction at 93.4°C is 0.707 g/cm³. Using this, the absolute viscosity is

$$\eta = \nu \rho = 0.5032 \times 0.707 = 0.356 \text{ cP}$$

On Fig. 3, go vertically from 10 000 psia until a viscosity of 0.356 cP is reached and then proceed horizontally until the reference line is reached. From the reference line proceed parallel to the curved lines until a UOPK factor of 11.95 is reached. From a K of 11.95 proceed horizontally to the left-hand axis and

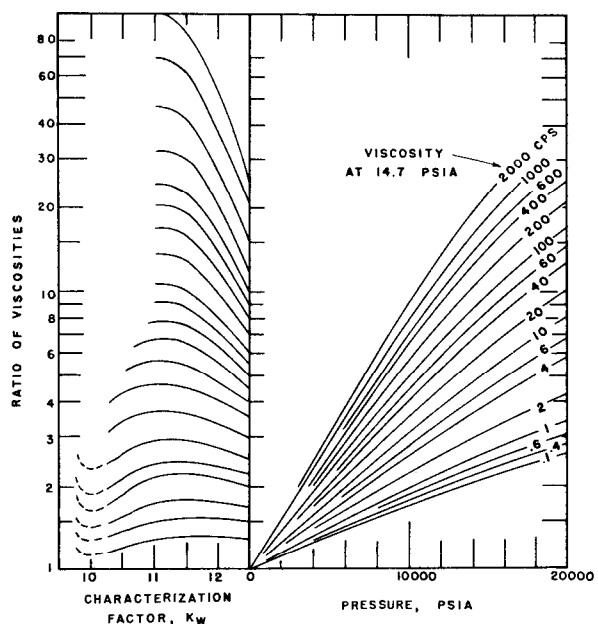


Figure 3 Effect of pressure on viscosity of mixtures of undefined liquid components. From Lockhart and Lenoir [40].

read off the viscosity ratio of 1.75. The absolute viscosity of the fraction at 93.4°C and 10 000 psia is

$$\eta = 0.356 \times 1.75 = 0.623 \text{ cP}$$

At moderate conditions the influence of temperature on gas viscosity is more significant than that of pressure. However, at extreme pressure there can be a significant influence of pressure on gas mixture viscosity. The procedure recommended by Dean and Stiel [14] appears to be the best way for predicting viscosity of gas mixtures under high-pressure conditions. Their recommended equation is

$$(\eta_m - \eta_m^0)\xi_m = 1.08 [\exp(1.439\rho_{cm}) - \exp(-1.111\rho_{cm}^{1.858})] \quad (6)$$

where η_m = high-pressure mixture viscosity in μP

η_m^0 = low-pressure mixture viscosity in μP

ρ_{cm} = pseudoreduced mixture density

ρ_m = mixture density in g mole/cm³

ρ_{cm} = pseudocritical mixture density in g mole/cm³

$$\xi_m = T_{cm}^{1/6}/M_m^{1/2}P_{cm}^{2/3}$$

In their evaluation of Eq. (6) Dean and Stiel evaluated the pseudocritical values for the mixture according to the modified Prausnitz and Gunn rules [42].

$$T_{cm} = \sum_i y_i T_{ci} \quad (7)$$

$$Z_{cm} = \sum_i y_i Z_{ci} \quad (8)$$

$$V_{cm} = \sum_i y_i V_{ci} \quad (9)$$

$$P_{cm} = \frac{Z_{cm}RT_{cm}}{V_{cm}} \quad (10)$$

$$\rho_{cm} = \frac{\sum_i \tilde{x}_i M_i}{\sum_i \tilde{x}_i V_{ci}} \quad (11)$$

Equation (6) has not been extensively tested. However, on the few binary mixtures used by Dean and Stiel Eq. (6) gave exceptional agreement with experimental measurement.

Example

Estimate the viscosity at 200 atm and 100° C of a mixture of ethane and propylene containing 50.1 mole % ethane. At 100° C and 1 atm Vargaftik[43] reports a value by Golubev [44] of 110.3 X 10⁻⁶ g/cm for the viscosity of the mixture.

The first step in the solution is to obtain the critical parameters for the two components in the gas mixture:

	T_c, K	$V_c, \text{m}^3/\text{mole}$	Z_c	M
Ethane	305.4	0.148	0.285	30.07
Propylene	305.0	0.181	0.273	42.081

From these values properties of the mixture are calculated according to the stated mixing rules:

$$M_m = 0.501 \times 30.07 + 0.499 \times 42.081 = 36.06$$

$$T_{cm} = 0.501 \times 305.4 + 0.499 \times 365 = 335.1$$

$$V_{cm} = 0.501 \times 0.148 + 0.499 \times 0.181 = 0.165$$

$$Z_{cm} = 0.501 \times 0.285 + 0.499 \times 0.273 = 0.279$$

$$P_{cm} = \frac{0.279 \times 0.08314 \times 335.1}{0.0165} = 218.55 \text{ kg/m}^3$$

$$\rho_{cm} = \frac{36.06}{0.165} = 218.55 \text{ kg/m}^3$$

In order to use Eq. (6) the density of the gas mixture at 100° C and 200 atm must be estimated. This can be done through the use of the compressibility factor determined by the use of reduced temperature and pressure:

$$T_r = \frac{373.15}{335.1} = 1.11 \quad P_r = \frac{200}{46.5} = 4.30$$

$$Z = 0.635$$

$$PV = ZnRT$$

$$200 \times 1.01325 \times V = 0.08314 \times 0.635 \times 373.15$$

$$V = 0.0972 \text{ m}^3/\text{kg mole}$$

$$\rho_m = 10.29 \text{ kg mole/m}^3 = 370.94 \text{ kg/m}^3$$

$$\rho_{Rm} = \frac{370.94}{218.55} = 1.6973$$

From Eq. (6) the mixture viscosity at 200 atm is

$$(\eta_m - 110.3)0.0334 = 1.08[\exp(1.439 \times 1.6973) - \exp(-1.111 \times 1.6973^{1.858})]$$

$$= 1.08(11.501 - 0.051)$$

$$\eta_m - 110.3 = 370.24$$

$$\eta_m = 480.5$$

The experimental value reported by Golubev is 500 X 10⁻⁶ g/cm.

C. Thermal conductivity

Early efforts at estimating mixture thermal conductivities used weighted averages based on mass or molecular

fractions. As these were shown to be inadequate, more sophisticated (usually empirical) models were suggested. Jamieson and Irving [45] suggested a procedure based on weight fractions:

$$\lambda_{\text{mix}} = x_1 \lambda_1 + x_2 \lambda_2 - (\lambda_2 - \lambda_1)(1 - \sqrt{x_2})x_2 \quad (12)$$

where 2 represents the component with larger thermal conductivity. Equation (12) gives better accuracy with nonaqueous mixtures. Errors will normally be less than 10% unless the mixture displays a minimum or maximum with composition.

Li [46] assumed: (1) Energy transport in the liquid state is by collision among molecules. Collision is due primarily to oscillation of neighboring molecules and the frequency of collision is approximately proportional to the number and size of neighboring molecules. (2) The interaction thermal conductivity is the harmonic mean of pure component values. The thermal conductivity then is

$$\lambda_m = \sum_i \sum_j \phi_i \phi_j \lambda_{ij} \quad (13)$$

where

$$\lambda_{ij} = 2(\lambda_i^{-1} + \lambda_j^{-1})^{-1}$$

$$\phi_i = \frac{\tilde{x}_i V_i}{\sum \tilde{x}_j V_j}$$

$$\sum \phi_i = 1.0$$

Li indicates that, for nonaqueous mixtures, critical volume may be substituted for molar volume without seriously influencing the accuracy of Eq. (13).

Example

Estimate the thermal conductivity of a mixture of methanol and water which contains 20 mole % water at 60°C. The molecular weight of methanol is 32.042 and the density at 60°C is 0.7555 g/cm³ [47]. The molecular weight of water is 18.016 and the density at 60°C is 0.9832 g/cm³ [48]. Equation (13) in expanded form for a binary mixture is

$$\lambda_m = \sum \phi_i - \phi_i \lambda_{ij} = \phi_1 \phi_1 \lambda_{11} + \phi_1 \phi_2 \lambda_{12} + \phi_2 \phi_2 \lambda_{22}$$

Calling methanol component 1 and water component 2 the molecular volumes are

$$V_1 = \frac{32.042}{0.7555} = 42.44 \text{ cm}^3/\text{g mole}$$

$$V_2 = \frac{18.016}{0.9832} = 18.32 \text{ cm}^3/\text{g mole}$$

The superficial volume fractions for each component are

$$\phi_2 = \frac{0.2 \times 18.32}{0.2 \times 18.32 + 0.8 \times 42.44} = 0.0974$$

$$\phi_1 = 0.9026$$

The thermal conductivity interactions are

$$\lambda_{11} = \frac{2(1)}{0.188^{-1} + 0.188^{-1}} = 0.188$$

$$\lambda_{12} = \frac{2(1)}{1(0.188^{-1} + 0.652^{-1})} = 0.2919$$

$$\lambda_{13} = 0.652$$

The mixture thermal conductivity then becomes

$$\begin{aligned} \lambda_m &= 0.9026 \times 0.9026 \times 0.188 \\ &\quad + 0.9026 \times 0.0974 \times 0.2919 \\ &\quad + 0.0974 \times 0.9026 \times 0.2919 \\ &\quad + 0.0974 \times 0.0974 \times 0.652 = 0.2107 \end{aligned}$$

According to Li [46] the experimental thermal conductivity determined by Rastorguev and Ganier [49] was 0.216 W/mK.

If the procedure of Jamieson and Irving in Eq. (12) is to be used the first step is to calculate the weight fractions: for methanol

$$X_1 = \frac{0.8 \times 32.042}{0.2 \times 18.016 + 0.8 \times 32.042} = 0.8768$$

For water

$$X_2 = \frac{0.2 \times 18.016}{0.2 \times 18.016 + 0.8 \times 32.042} = 0.1232$$

The thermal conductivity for the mixture then becomes

$$\begin{aligned} \lambda_{m, \text{est}} &= 0.1232 \times 0.652 + 0.8768 \times 0.188 \\ &\quad - (0.652 - 0.188)(1 - 0.1232)0.1232 \end{aligned}$$

$$\lambda_m = 0.0208$$

Li indicates that, for nonaqueous mixtures, critical volume may be substituted for molar volume without seriously influencing the accuracy of Eq. (13).

For mixtures of undefined hydrocarbon components the thermal conductivity may be estimated by

$$\lambda = 1.744 \times 10^{-2} - 1.493 \times 10^{-5} T \quad (14)$$

where λ is the thermal conductivity in W/m² K/m and T is the temperature in K.

Equation (14) provides only one thermal conductivity value regardless of boiling range, density, or Watson characterization factor. This seems an oversimplification and has been shown experimentally to be incorrect [50]. However, it will provide estimates of thermal conductivity for crude fractions that are

generally within $\pm 25\%$ of the true thermal conductivity of the mixture. It is limited to boiling range cuts distilled from raw crude. It should not be used for internal refinery streams that contain substantial quantities of unsaturated hydrocarbons.

The effect of pressure on liquid thermal conductivity is small over normal pressure ranges.

D. Heat capacity

There are no techniques for estimating the heat capacity of mixtures without knowledge of pure component values. When pure component data are available, the mixture value is taken as the unweighted average of the pure component values, keeping in mind the necessity for dimensional consistency. This approach ignores heat of mixing and similar effects. For this reason, large errors could be generated when the heat of mixing is **nonzero**. For hydrocarbons and nearby homologs, the assumption is good and heat capacities should be within 10% although few mixture heat capacity data are available for comparison.

For undefined mixtures, liquid heat capacity may be estimated by use of Fig. 4 which was adapted from a chart by Maxwell [51]. Density and true boiling point range for the **mixture** are required for use of Fig. 4. At **pseudo**-reduced temperatures below 0.85, the isobaric heat capacity of undefined mixtures can be estimated as [52]:

$$C_p = A_1 + A_2 T + A_3 T^2$$

where C_p is the isobaric heat capacity for the liquid petroleum fraction in Btu/lb $^{\circ}\text{F}$.

$$A_3 = -1.171\,26 + (0.023\,722 + 0.024\,907\,SG)K \\ + \frac{(1.149\,82 - 0.046\,535\,K)}{SG}$$

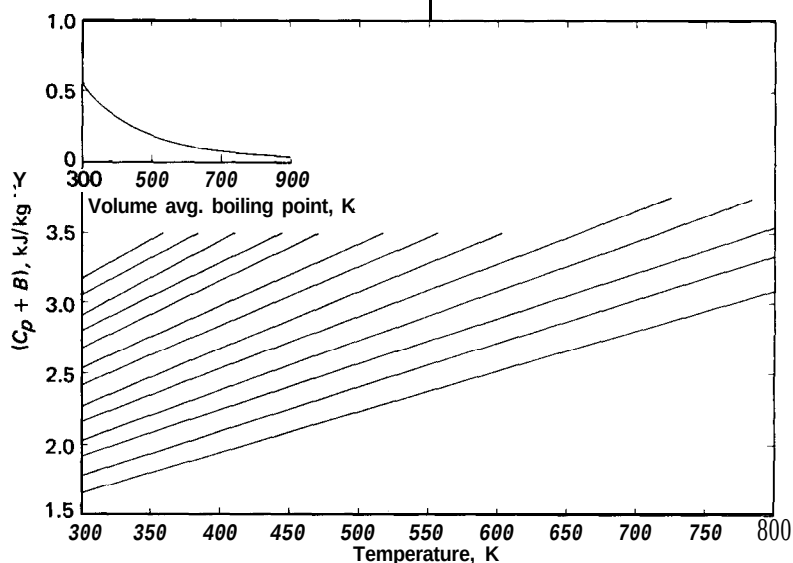


Figure 4 Specific heat capacity of hydrocarbon liquid mixtures $C_p = (C_p + B) - B$.

$$A_2 = 10^{-4}(1.0 + 0.824\,63dK) \left(1.121\,72 - \frac{0.276\,34}{SG} \right)$$

$$A_2 = -10^{-8}(1.0 + 0.824\,63K) \left(2.902\,7 - \frac{0.709\,58}{SG} \right)$$

T_r = reduced temperature, T/T_{pc}

T = temperature in $^{\circ}\text{R}$

T_{pc} = pseudocritical temperature, $^{\circ}\text{R}$

K = Watson characterization factor (see p. 5.2.1-7)

SG = specific gravity 60F/60F

E. Specific heat capacity of gas mixtures

For mixtures of ideal gases the heat capacity can be estimated as either the mole fraction or weight fraction average depending upon which heat capacity is available. The methods suggested in Sec. 5.4 can be used to obtain the pure component values.

For mixtures of real gases the departure from ideal gas behavior must be accounted for. Figure 5 shows the molal heat capacity departure of real gases from ideal gas behavior as a function of reduced temperature and pressure [53].

Example

Estimate the heat capacity of a gas mixture that is 40 mole % methane and 60 mole % ethane. The mixture is at 40°C and at a pressure of 7 MPa. From the GPA data book [54] the **molal** ideal gas state heat capacity for methane is 36.21 and for ethane 54.21 kJ/kg mole K.

The solution first requires estimating the mole fraction average heat capacity, critical temperature, and critical pressure. The calculation is shown in the following table.

Comp	Mole fraction	C_p , kJ/kg mole K	C_{pm}	T_c , K	T_{cm} , K	P_c , MPa	R_{cm} , MPa
C_1	0.4	36.21	14.48	190.6	16.2	4.60	1.84
C_2	0.6	54.21	32.53	305.9	183.5	4.88	2.93
			47.01		259.7		4.77

Critical temperature and pressure values were taken from the American Petroleum Institute [55].

The reduced temperature is

$$T_r = \frac{313.2}{259.7} = 1.21$$

The reduced pressure is

$$P_r = \frac{7}{4.77} = 1.47$$

Using these values at reduced temperature and pressure the heat capacity departure as read from Fig. 5 is

$$C_p - C_p^* = 9.7 \text{ Btu/lb mole } ^\circ\text{R} = 40.6 \text{ kJ/kg mole K}$$

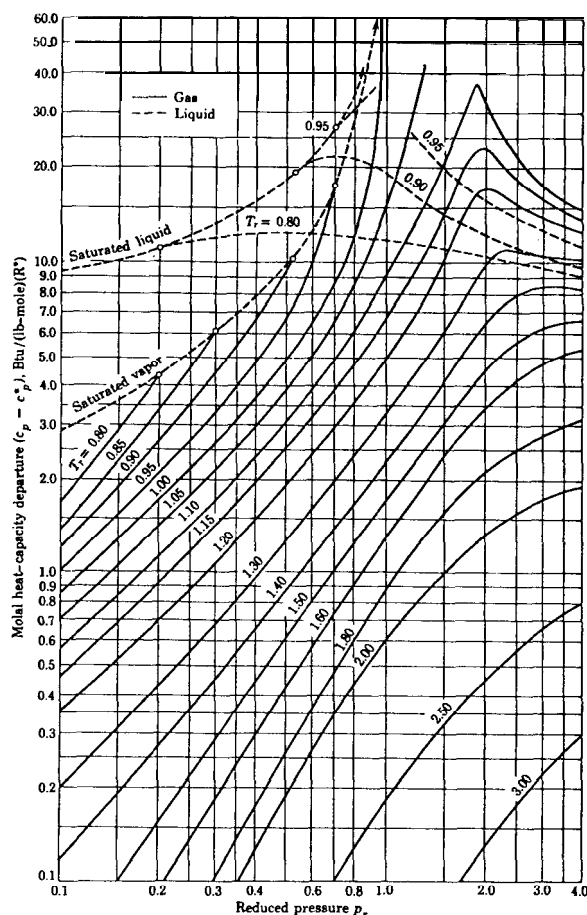


Figure 5 Real gas molal heat capacity departure. From Leyderson et al. [55].

The real gas mixture heat capacity is

$$c_{pm} = 47.01 + 40.6 = 87.61 \text{ kJ/kg mole K}$$

F. Mixtures of undefined components

Figure 6 is taken after the work of Fallon and Watson [56] as presented in Standards of Tubular Exchanger Manufacturers Association [57]. It provides the specific heat capacity of petroleum fractions as a function of the Watson characterization factor and temperature. The specific heat capacity values from Fig. 6 are for low-pressure use and compare with the ideal gas state heat capacity for pure components. Figure 5 can be used to adjust these values for real gas pressure effects if pseudocritical values are estimated as outlined in Sec. 5.2.1(B).

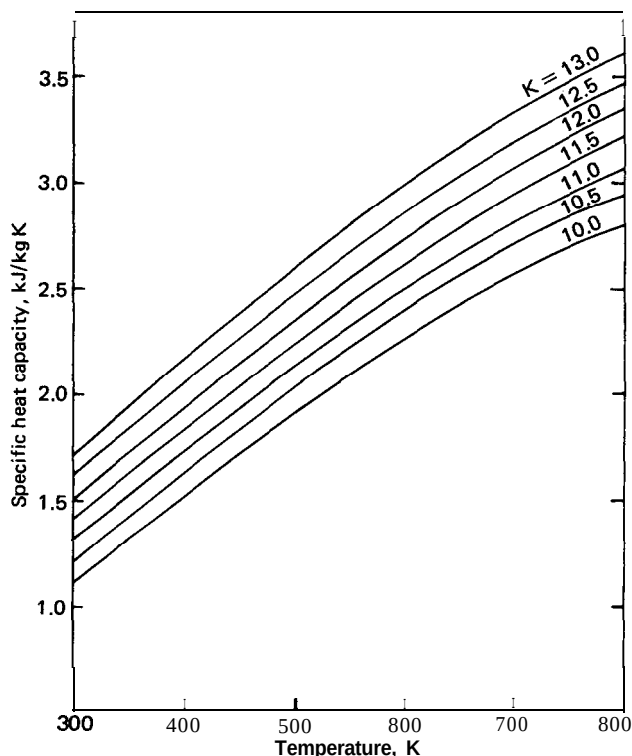


Figure 6 Specific heat capacities of vapor mixtures of undefined hydrocarbon components.

Nomenclature for Section 5.2.3 appears at the beginning of Part 5. References appear at the end of Section 5.2.5.

5.2.4

Interfacial tension

R. N. Maddox

■ In the literature, there is great confusion in using terms to describe the pulling on molecules at the interface between two phases. In this discussion surface tension will be applied to those instances when the gas phase is air; interfacial tension will apply to instances when the gas phase is the equilibrium vapor of the liquid. Liquid-liquid and liquid-solid phases will not be considered.

For most process design applications, the quantity of interest is the interfacial tension. Seldom do we have process fluids under conditions such that they are in contact with air at atmospheric pressure. Most pure component measurements, until recently at least, were made on the laboratory bench and the engineer is limited to the use of surface tension.

For binary mixtures, when pure component values of surface tension are known, the mixture surface tension may be estimated by simple mole fraction average :

$$\sigma_m = \sum x_i \sigma_i \quad (1)$$

When the mixture is at high pressure, or when pure component values are not available, the Macleod-Sugden [56] relationship can be used to estimate mixture surface tension:

$$\sigma_m^{1/4} = \sum (P_i)(\rho_{Lm} \tilde{x}_i - \rho_{Vm} \tilde{y}_i) \quad (2)$$

where P is the Parachor number and m is the mixture property. If density values for the mixture are not available, but it is made up of defined components, a

modification [57] of the Macleod-Sugden equation may be used:

$$\sigma_m \frac{P_m}{R_{Dm}} \frac{n_m^2 - 1}{n_m^2 + 2} \quad (3)$$

where R_D is the molar refraction and n is the refractive index. Mixture values of R_D , P , and n are taken as mole fraction averages.

There is little to choose in accuracy among the three estimating techniques. They are subject to errors as large as 10%. None of the three is recommended for aqueous mixtures.

Because of the polar characteristics of water, aqueous mixtures present a special problem for estimating surface tension. Three different phases may be encountered—the vapor phase, the liquid phase, and the boundary phase—which may have quite different characteristics from the bulk of the liquid. For estimating surface tension of aqueous mixtures, the procedure of Tamura et al. [58] is recommended.

$$\sigma_m^{1/4} = \psi_w^\sigma \sigma_w^{1/4} + \psi_o^\sigma \sigma_o^{1/4} \quad (4)$$

ψ_w^σ is the superficial volume fraction of water in the surface layer and is defined as

$$\psi_w^\sigma = \frac{\tilde{x}_w^\sigma V_w}{V^\sigma} \quad (5)$$

$$\psi_o^\sigma = \frac{\tilde{x}_o^\sigma V_o}{V^\sigma} \quad (6)$$

For calculating the superficial surface volume fractions,

equilibrium between the surface and bulk phases is assumed.

$$C = B + D \quad (7)$$

$$B = \log \frac{\psi_w^q}{\psi_o} \quad (8)$$

$$C = \log \frac{(\psi_w^o)^q}{\psi_o^o} \quad (9)$$

$$D = 0.441 \frac{q}{T} \left(\frac{\sigma_o V_o^{2/3}}{q} \right) - \sigma_w V_o^{2/3} \quad (10)$$

$$\psi_w = \frac{\tilde{x}_w V_w}{\tilde{x}_w V_w + \tilde{x}_o V_o} \quad (11)$$

$$\psi_o = \frac{x_o V_o}{\tilde{x}_w V_w + \tilde{x}_o V_o} \quad (12)$$

where $\tilde{x}$ = bulk mole fraction of component

V = molar volume of component in $\text{cm}^3/\text{g mole}$

σ = surface tension

T = temperature, K

q = constant depending on type and size of organic component. Values in Table 1.

ψ = superficial volume fraction

o = a subscript denoting organic component

w = a subscript denoting water

σ = a superscript denoting the surface zone between the liquid and vapor phase

Reid et al. [58] report errors less than 10% when q is less than 5 with errors as large as 20% for values of q larger than 5. Equation (4) can be applied to organic mixtures by letting q equal the ratio of molar volumes of solute to solvent.

Example

Calculate the interfacial tension of a 30 mole % acetone-water mixture at 150°F . According to Miller [59] the surface tension of water is 66.84 dynes/cm and the surface tension of acetone is 17.62 dynes/cm at 150°F (65.6°C). The molecular weight of acetone and water are 58.1 and 18.016, while the densities are 0.737 9 and 0.980 3 [60].

The molar volumes are calculated from the molecular weight and density:

$$V_o = \frac{58.1}{0.7379} = 78.74 \text{ cm}^3/\text{g mole}$$

$$V_w = \frac{18.016}{0.9803} = 18.38 \text{ cm}^3/\text{g mole}$$

The superficial volume fractions for water and acetone are calculated from Eqs. (11) and (12):

$$\psi_w = \frac{0.7 \times 18.38 + 0.3 \times 78.74}{0.7 \times 18.38 + 0.3 \times 78.74} = 0.3526$$

$$\psi_o = \frac{0.3 \times 78.74}{0.7 \times 18.38 + 0.3 \times 78.74} = 0.6474$$

Using a value of $q = 2$ for acetone from Table 1 the constant B is evaluated from Eq. (8):

$$B = \log \frac{(0.3524)^2}{0.6476} = \log 0.1918 = -0.7172$$

and the constant D from Eq. (1):

$$D = 0.441 \frac{2}{338.7} \left[\frac{17.62(78.74)^{2/3}}{2} - 66.84(78.74)^{2/3} \right]$$

$$= 0.002604(161.85 - 1227.9) = -2.776$$

The constant C is evaluated from Eq. (7):

$$C = B + D = -0.7172 - 2.776 = -3.4932$$

However, constant C is also expressed in terms of the interphase composition in Eq. (9). Since by definition the superficial volume fractions must sum to unity

$$\psi_o^o + \psi_w^o = 1.0$$

The superficial volume fractions at the interface can be calculated by combination of Eqs. (7) and (9).

$$\frac{\log(\psi_w^o)^q}{\psi_o} = -3.4932$$

$$\frac{\log(\psi_w^o)^2}{1 - \psi_w^o} = -3.4932$$

Solving for the superficial volume fractions at the interface:

$$\psi_w^o = 0.0178$$

$$\psi_o^o = 0.9822$$

Table 1 Values of constant q for use with procedure of Tamura et al. [58]

Materials	4	Example
Fatty acids, alcohols	Number of carbon atoms	Acetic acids, $q = 2$
Ketones	One less than the number of carbon atoms	Acetone, $q = 2$
Halogen derivatives of fatty acids	Number of carbons times ratio of molal volume of halogen derivative to parent fatty acid	Chloroacetic acid, $q = 2 \frac{V_b(\text{chloroacetic acid})}{V_b(\text{acetic acid})}$

The mixture interfacial tension at 150° F can now be calculated from Eq. (4);

$$\sigma_m^{1/4} = 0.017 \cdot 8(66.84)^{1/4} + 0.982 \cdot 2(17.62)^{1/4}$$

$$\sigma_m = 18.12 \quad (\text{experimental value is } 23.1)$$

Miller [59] gives an experimentally determined value

of 23.1 dynes/cm which differs by more than 20% from the calculated value.

Surface tensions for mixtures of undefined components can be estimated through the Parachor number. Equation (2) is used with the Parachor number being determined by [61]

$$P = 40 + 2.38 (\text{mol. wt.}) \quad (13)$$

Nomenclature for Section 5.2.4 appears at the beginning of Part 5. References appear at the end of Section 5.2.5.

5.2.5

Diffusion coefficients

R. N. Maddox

A. Introduction

Diffusion refers here to transport of a material within one phase due to molecular characteristics alone: there is no external force or turbulence causing the transport. Diffusion can be caused by gradients within the phase created by a number of variables. The only case considered here is diffusion caused by a concentration gradient. In a binary mixture, if component **A** diffuses from position 1 to position 2 at a given rate, then to maintain equal molal flow, component **B** must diffuse at the same rate in the opposite direction. If F^m is the molal flux, the diffusion coefficient is defined as

$$F_A^m = -CD_{AB}\nabla x_A \quad (1)$$

$$F_B^m = -CD_{BA}\nabla x_B \quad (2)$$

where C = total molar concentration

F^m = the molar flux due to diffusion

D = the diffusion coefficient

The activity corrected diffusion coefficient is

$$A_{AB} = \frac{D_{AB}}{(a \ln a_A)/(\partial \ln \tilde{x}_A)} \quad (3)$$

For gases, $D_{AB} = \Delta_{AB}$ because concentration effects are much less for gases than for liquids.

B. Diffusion in liquids

For diffusion of components through dilute solutions, the equation proposed by Wilkie and Chang [62] is recommended:

$$D_{AB} = \frac{1.17 \times 10^{-16} (\phi \tilde{M}_B)^{1/2} T}{\eta_B \tilde{v}_A^{0.6}} \quad (4)$$

where D_{AB} = diffusion coefficient of solute **A** in low concentrations in solvent **B** (m^2/s)

$\tilde{M}_B$ = molecular weight of solute **B**

T = temperature (K)

η_B = viscosity Of the solvent **B** at temperature T (Ns/m^2)

ϕ = the associated factor for solvent **B** (= 2.6 for water; = 1.0 for nonassociated solvents)

$\tilde{v}_A$ = molar volume of solute at its normal boiling point (m^3/kmol)

For nonassociated solvents, Eq. (4) can be used with a value of 1.0 for ϕ .

Tyn [64] developed a nomograph for estimating diffusion coefficients for various solute-solvent combinations at different temperatures. His approach was to assume a linear relationship between the temperature at which a liquid mixture will have a given diffusion coefficient and the temperature at which water exhibits the same coefficient. His nomograph is shown in Fig. 1. X and Y coordinates for different components are shown in Table 1. The use of the nomograph is best illustrated with an example (see below).

Example

Calculate the liquid diffusion coefficient for methanol solute in water solvent at 15°C . Here, $\tilde{M}_B = 18.016$, $\eta_B = 1.146 \times 10^{-3}$, $\phi = 2.6$, $T = 288.15 \text{K}$

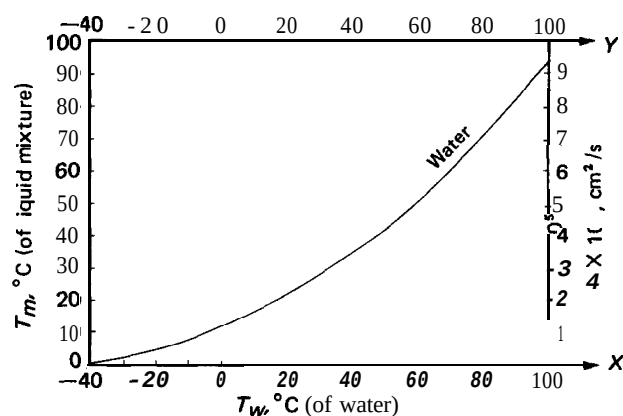


Figure 1 Nomograph for estimating liquid diffusion coefficients

and (from the table for methanol in Sec. 5.5.1) $\tilde{v}_A = 32.00/751.0 = 0.0426 \text{ m}^3/\text{k mole}$.

Using Eq. (4), the diffusion coefficient is:

$$D_{AB} = \frac{(1.17 \times 10^{-16})(2.6 \times 18.016)}{(1.146 \times 10^{-3})(0.0426)^{0.6}} (2.88.15)$$

$$= 1.34 \times 10^{-9} \text{ m}^2/\text{s}$$

According to Bretsznajder [65] the experimental value is $1.28 \times 10^{-9} \text{ m}^2/\text{s}$.

If Fig. 1 is to be used, the values of X and Y must be determined from Table 1. For the methanol-water system the X coordinate is -12.0 and the Y coordinate is 80 . These two points are connected with a straight line. From the intersection of that straight line

Table 1 Mixture coordinates for use with Fig. 1

Binary liquid mixture				
No.	Solute	Solvent	X	Y
1	Methane	Water	-11.5	76.5
2	Ethane	Water	-16.0	63.8
3	Propane	Water	-21.0	62.5
4	Butane	Water	-22.0	56.8
5	Pentane	Water	-23.0	51.0
6	Cyclohexane	Water	-21.5	41.0
7	Cyclopentane	Water	-19.0	46.0
8	Methylcyclopentane	Water	-22.0	41.0
9	Acetylene	Water	0.0	70.0
10	Benzene	Water	-15.0	55.0
11	Toluene	Water	-21.5	45.5
12	Ethyl benzene	Water	-21.5	41.0
13	Methanol	Water	-12.0	80.0
14	Ethanol	Water	-14.0	50.5
15	<i>n</i> -Propanol	Water	-19.5	56.0
16	<i>i</i> -Propanol	Water	-20.0	53.0
17	<i>n</i> -Butanol	Water	-21.0	50.0
18	<i>i</i> -Butanol	Water	-27.0	60.0
19	Ethyleneglycol	Water	-16.0	51.0
20	Acetone	Water	-11.0	44.5
21	Manitol	Water	-27.0	24.0
22	Alanine	Water	-22.0	40.5
23	Acetamide	Water	-18.0	64.0
24	Butylamide	Water	-22.5	59.5
25	Formamide	Water	-11.0	73.5
26	Glycoamide	Water	-17.0	49.0
27	Propioamide	Water	-22.0	63.5
28	Urea	Water	-13.5	58.0
29	Triethyleneglycol	Water	-28.0	41.0
30	Iodine	Ethanol	-10.5	47.5
31	Water	Ethanol	-19.0	53.5
32	Acetic acid	Carbon tetrachloride	-2.5	35.5
33	Formic acid	Carbon tetrachloride	+4.5	44.5
34	Benzene	Carbon tetrachloride	-6.5	41.0
35	Cyclohexane	Carbon tetrachloride	-8.0	36.5
36	Heptane	Benzene	+3.0	63.0
37	Methanol	Benzene	+25.5	100.0
38	Ethanol	Benzene	+12.0	92.0
39	Benzoic acid	Benzene	-7.5	43.0

Table 1 Mixture coordinates for use with Fig. 1 (Continued)

Binary liquid mixture						
No.	Solute		Solvent		X	Y
40	Acetic	acid	Toluene	+	7.0	64.5
41	Formic	acid	Toluene	+	19.5	52.5
42	Cyclohexane		Toluene	+	1.5	81.0
43	Methylcyclohexane		Toluene	+	5.0	69.0
44	Aniline		Toluene	+	1.0	67.0
45	Acetic	acid	Acetone	+	23.0	84.0
46	Water		Acetone	+	49.5	97.0
47	Chloroform		Acetone	+	26.5	92.0
48	Iodine		n-Octane	+	16.0	69.0
49	Toluene		Aniline	—	36.0	28.0
50	Benzene		Heptane	+	21.5	93.0
51	Toluene		Heptane	+	28.5	87.0
52	Acetone		Chloroform	+	8.0	66.5
53	Toluene		Methylcyclohexane	—	3.0	50.0
54	Carbon tetrachloride		Cyclohexane	—	1.5	50.0
55	Iodine		Cyclohexane		0.0	53.0
56	Benzene		Cyclohexane	—	1.5	63.0
57	Toluene		Cyclohexane	—	2.5	42.0
58	Chlorobenzene		Bromobenzene	—	7.5	33.5
59	Toluene		Chlorobenzene	—	1.0	49.0

with the 15° C horizontal line, extend vertically to the curve labeled water and then horizontally to the right-hand axis to read a diffusion coefficient of:

$$D_{AB} = 1.25 \times 10^{-5} \text{ cm}^2/\text{s}$$

C. Diffusion in gases

For gaseous diffusion coefficients in binary mixtures, the procedure of Fuller et al. [67] is recommended. They utilized a group contribution approach to define special diffusion volumes which are used to predict diffusion coefficients from:

$$D_{AB} = \frac{1.013 \times 10^{-7} T^{1.75} (1/\tilde{M}_A + 1/\tilde{M}_B)^{1/2}}{P \left[\left(\sum_A v_i \right)^{1/3} + \left(\sum_B v_i \right)^{1/3} \right]^2} \quad (8)$$

where D_{AB} = binary diffusion coefficient, m^2/s

v_i = special diffusion parameters to be summed over atoms, groups, and structural features of the diffusing species

$\tilde{M}$ = molecular weight, kg/kmole

P = pressure, bar

Example

Determine the gas phase diffusivity of methane through water vapor at a temperature of 352.3 K and

one atmosphere (1.013 bar) pressure. The molecular weight of water is 18.016 and the molecular weight of methane is 16.043. Using values from Table 2 the special molecular diffusion volumes for methane and water are calculated as:

$$v_{\text{H}_2\text{O}} = 12.7$$

$$v_{\text{CH}_4} = v_{\text{C}} + 4 v_{\text{H}} = 16.5 + 4(1.98) = 24.42$$

Using Eq. (8) the diffusivity of methane gas through water vapor is calculated as

Table 2 Diffusion volumes for use with Eq. (8)

Atomic and structural diffusion volume increments			
C	16.5	(Cl)	19.5
H	1.98	(S)	17.0
O	5.48	Aromatic or heterocyclic rings	— 20.2
(N)	5.69		
Diffusion volumes of simple molecules			
H ₂	7.07	c o ,	26.9
D ₂	6.70	N ₂ O	35.9
He	2.88	NH ₃	14.9
N ₂	17.9	H ₂ O	12.7
O ₂	16.6	(CCl ₂ F ₂)	114.8
Air	20.1	(SF ₆)	69.1
Ne	5.59		
Ar	16.1	(Cl ₂)	37.7
Kr	22.8	(Br ₂)	67.2
(Xe)	37.9	(SO ₂)	41.1
c o	18.9		

D_{AB}

$$= \frac{1.013 \times 10^{-7} (352.3)^{1.75} (1/18.016 + 1/16.043)^{1/2}}{1.013(12.7^{1/3} + 24.42^{1/3})^2}$$

$$= 0.3589 \times 10^{-4} \text{ m}^2/\text{s}$$

Fuller et al. report an experimental measurement by Schwertz and Brown of $0.356 \times 10^{-4} \text{ m}^2/\text{s}$.

Nomenclature for Section 5.4.5 appears at the beginning of Part 5.

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5.3

Properties of rheologically complex media

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5.3.1

Disperse compositions

Z. P. Shulman

A. General statements

Non-Newtonian behavior is inherent in the majority of moderately and strongly concentrated suspensions and emulsions: lubricants, fuel liquid mixtures (carbon, peat, mazut, shale), liquid-disperse rocket and nuclear fuels, paper, ceramic, concrete, asphalt, and food masses, etc. Dilute polymer solutions and disperse compositions are generally characterized by the Newtonian viscosity depending only on the volume content of the prescribed-shape particles but not on the stress-strain state. The rheological properties, hydrodynamics, and convective heat transfer of non-Newtonian media are beyond the scope of this section. They are considered in detail in monographs [1-5] and in review [6]. Note that at present there are no general and reliable methods for calculating the rheological properties of compositions by the prescribed individual properties and the content of their components.

The relationships used below for thermophysical properties are based on the simplest physical models disregarding disposition of phases, surface phenomena, particle contacts, and structurization. Nevertheless, simplicity being their advantage, they allow quite reliable qualitative estimates.

B. Two-component compositions

Depending on the relationships between individual thermal conductivities, compositions may be grouped into four classes [7]:

Relations given in Sec. 5.3.1 also refer to the mixtures of solid particles, powders, and porous media.

- Class I: $\lambda_c \gg \lambda_d$ or $\lambda_c/\lambda_d > 100$;
- Class II: $\lambda_d \gg \lambda_c$ or $\lambda_d/\lambda_c > 100$;
- Class III: $1 < \lambda_c/\lambda_d < 100$;
- Class IV: $1 < \lambda_d/\lambda_c < 100$.

Indices c and d denote continuous and discrete phases. The systems of Classes II and IV are those most encountered, e.g., metal suspensions. At present there are no correlations that are equally valid to the above four classes.

When $\lambda_c > \lambda_d$

$$\frac{1}{\lambda} = \frac{2}{\sqrt{-G(\lambda_d - \lambda_c)[\lambda_c + B(\lambda_d - \lambda_c)]}} \tan^{-1} \frac{B}{2} \times \sqrt{\frac{-G(\lambda_d - \lambda_c)}{\lambda_c + B(\lambda_d - \lambda_c)}} + \frac{1 - B}{\lambda_c} \quad (1)$$

When $\lambda_d > \lambda_c$

$$\frac{1}{\lambda} = \frac{1}{\sqrt{G(\lambda_d - \lambda_c)[\lambda_c + B(\lambda_d - \lambda_c)]}} \times \ln \frac{\sqrt{\lambda_c + B(\lambda_d - \lambda_c)} + (B/2)\sqrt{G(\lambda_d - \lambda_c)}}{\sqrt{\lambda_c + B(\lambda_d - \lambda_c)} - (B/2)\sqrt{G(\lambda_d - \lambda_c)}} + \frac{1 - B}{\lambda_c} \quad (2)$$

Here $B = \sqrt{3z_d/2}$ and $G = -4\sqrt{2/3z_d}$ are the parameters for the disperse phase content. Equation (2), within $\lambda_d \gg \lambda_c$, reduces to the simple formula, not including λ_d ,

$$\lambda = \frac{\lambda_c}{1 - B} = \frac{\lambda_c}{1 - \sqrt{3z_d/2}} \quad (3)$$

For spherical particle dispersions (Classes I, III, and IV) with volume concentrations $z_d < 0.1$, the Maxwell formula [8] is sufficiently accurate:

$$\frac{\lambda}{\lambda_c} = \frac{\lambda_d + 2\lambda_c - 2z_d(\lambda_c - \lambda_d)}{\lambda_d + 2\lambda_c + z_d(\lambda_c - \lambda_d)} \quad (4)$$

Equation (4), at $\lambda_d \gg \lambda_c$, is simplified to

$$\lambda = \lambda_c \frac{1 + 2z_d}{1 - z_d} \quad (5)$$

Suspensions of nonspherical well heat-conducting particles (Class II) are governed by the Hamilton formula [9]:

$$\lambda = \frac{\lambda_c [\lambda_d + (n-1)\lambda_c - (n-1)(\lambda_c - \lambda_d)z_d]}{\lambda_d + (n-1)\lambda_c + (\lambda_c - \lambda_d)z_d} \quad (6)$$

Here $n = 3/\psi$, where ψ is the sphericity factor. For spherical particles $\psi = 1$. For multicomponent compositions we have

$$\lambda = \lambda_1 \frac{1 - \sum_{i=2}^m z_i(n_i - 1)(\lambda_1 - \lambda_i)}{1 + \sum_{i=2}^m z_i(\lambda_1 - \lambda_i)/\lambda_i + (n_i - 1)\lambda_i} \quad (7)$$

Here $n_i = 3/\psi_i$ is the nonsphericity factor for the i th component. The first component is usually a solid phase. Depending on the thermal conductivity ratios for the components, three-phase compositions may be divided into seven classes:

Class I: $\lambda_{d1}/\lambda_c > 100$; $\lambda_{d2}/\lambda_c > 100$. These systems are composed of good heat-conducting particles and may be treated as two-phase compositions of Class II with volume content $z_d = z_{d1} + z_{d2}$. The calculation is made using Eqs. (3) and (7).

Class II: $\lambda_{d1}/\lambda_c > 100$; $10 < \lambda_{d2}/\lambda_c < 100$. Equation (7) or Eqs. (2) and (3) are used for two-phase mixtures. Since $\lambda_d \gg \lambda_c$ and $\lambda_{d1} \gg \lambda_{d2}$, the composition may be considered to be two-phase with particle dispersion of phase 2 in the initial continuum as medium and component 1 as disperse phase.

Class III: $10 < \lambda_{d1}/\lambda_c < 100$; $10 < \lambda_{d2}/\lambda_c < 100$. The calculation is made by Eq. (7) or (2). In this case $z_{c2} = z_{d2} + z_c$; $z_d = z_{d1}$ and $\lambda_d = \lambda_{d1}$.

Class IV: $\lambda_{d1}/\lambda_c \sim 10$; $\lambda_{d2}/\lambda_c \sim 10$.

Class v: $\lambda_{d1}/\lambda_c \sim 10$; $\lambda_{d2}/\lambda_c \sim 1$.

Class VI: $\lambda_{d1}/\lambda_c \sim \lambda_{d2}/\lambda_c \sim 1$.

Thermal conductivity of liquid compositions of Classes IV-VI is calculated by the formulas adopted for Class III, i.e., by Eqs. (7) and (2). Equation (1) is also valid for the mixtures of Class VI.

Class VII: $\lambda_{d1}/\lambda_c < 1$ and/or $\lambda_{d2}/\lambda_c < 1$. Thermal conductivity of the compositions of this class can be also calculated by Eqs. (1), (2), and (7).

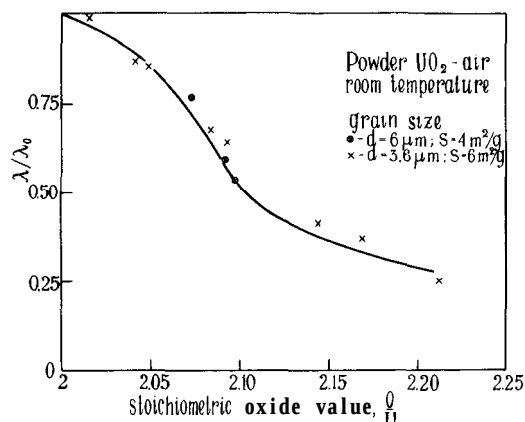


Figure 1 Effect of uranium oxidation degree on thermal conductivity of nuclear suspension.

C. Nuclear fuel suspensions

In these suspensions [10] uranium oxide particles are dispersed in liquid metals, namely, in sodium or sodium potassium mixture. Since both components possess good thermal conductivity, $5 < \lambda_c/\lambda_d < 10$. However, the direct use of Eq. (1) can give errors due to disregard for the uranium oxidation degree, i.e., due to the stoichiometric shift to higher oxides up to U_3O_8 inclusive (Fig. 1). Nuclear third-class suspensions are governed by

$$\frac{\lambda}{\lambda_c} = s(2-s) + \frac{(1-s)^2}{1-s + (\lambda_d/\lambda_c)s} \frac{\lambda_d}{\lambda_c} \quad (8)$$

$$\frac{\lambda}{\lambda_c} = \frac{2\epsilon(3-2\epsilon)^{\lambda_d/\lambda_c}}{3-\epsilon + \epsilon^{\lambda_d/\lambda_c}} \quad (9)$$

These equations are based on the representation of isotropic compositions of cubic [Eq. (8)] and spherical [Eq. (9)] particles covered uniformly with liquid films. The parameter, $s = 1 - (1 - \epsilon)^{1/3}$, denotes the relative

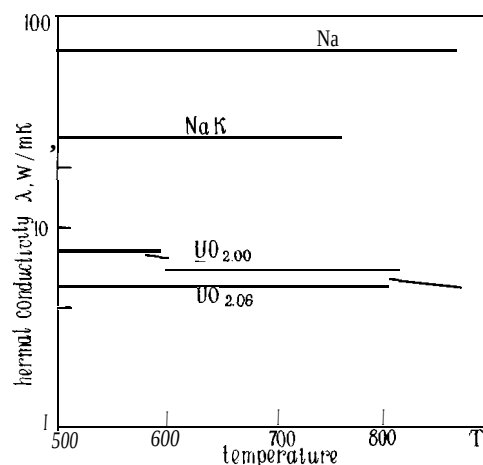


Figure 2 Thermal conductivity of nuclear suspension component vs. temperature.

liquid-phase dimension expressed in terms of the porosity. Figure 2 shows temperature dependencies of thermal conductivity for nuclear composition components **while** Fig. 3 illustrates the experimental **verification** of the theory. The porosity ϵ , the liquid-phase to suspension-volume ratio, is related to the volumetric fraction of a solid phase by $z_d = 1 - \epsilon$. Thermal conductivity of nuclear fuel suspensions is sharply raised with increasing solid-phase content. Equations (8) and (9) agree well with experiment.

D. Petroleum

Petroleum represents a polyfractional multicomponent system. Its density ranges from 730 to 1 040 kg/m³. Heavy (non-Newtonian) petroleum ($\rho > 900$ kg/m³),

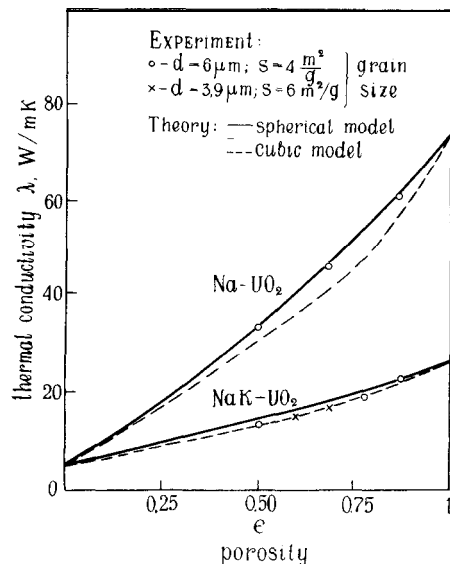


Figure 3 Thermal conductivity of typical nuclear suspensions vs. uranium dioxide content (solid phase).

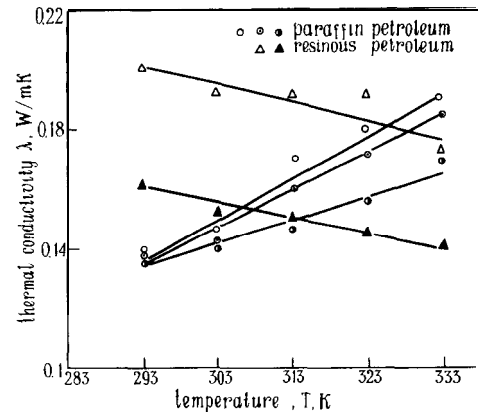


Figure 4 Petroleum thermal conductivity vs. paraffins and resins.

containing a great number of solid hydrocarbons (paraffins, resins, asphaltenes), possesses highly anomalous viscosity and viscoplasticity. Petroleum is subjected to various thermal effects during production, storage, transportation, refining, and utilization. In particular, petroleum, mazut, and bitumen are heated before being pumped.

Large-scale production and consumption of petroleum predetermine the importance of its thermophysical properties. Cragoe's formula [Eq. 5.3.3(3)] is still widely useful for non-Newtonian petroleum but gives underestimated values of thermal conductivity for heavy Middle-Asia petroleum [11]. Also, with increasing density the value of A increases rather than diminishing. The function $\lambda(T)$ also differs from Cragoe's formula. In particular, thermal conductivity of resinous petroleum decreases with heating (Fig. 4). For paraffin petroleum $\lambda(T)$ is an increasing function, which can be attributed to paraffin-particle melting. The slope of the above temperature dependencies is affected by the composition of solid hydrocarbons.

Nomenclature for Section 5.3. I appears at the beginning of Part 5. References appear at the end of Section 5.3.8.

5.3.2

Classification of lubricants

Z. P. Shulman

■ In power plants and heat exchangers, lubricants are used as test media, specifically, high-temperature heat carriers, heat-insulating materials, fuel mixtures, etc. [12-17].

Organic petroleum oils are a mixture of hydrocarbons and their derivatives. Animal and plant oils are primarily used as additives to petroleum oils. Synthetic oils serve as petroleum oil substitutes at very low and high temperatures for cases of elevated fire danger, etc. The oil quality is improved by alloying additives such as **antiwear** and viscosity additives, set point additives (for lowering solidification temperature), detergents, **anti-corrosion** additives, etc. At positive temperatures, oils serve as Newtonian fluids. **Polymer** thickening of oils produces a viscous anomaly.

Plastic lubricants consist of a homogeneous medium (oil) and a solid phase: fatty acid salts (soaps), solid hydrocarbons, silica gels, and **bentonites** with additives and solid additions (graphite, metal powders, etc.). Very long particles form a mobile structure that undergoes reversible destruction beyond the yield stress, and the lubricant flows as a **rheologically** complex nonlinear viscoplastic fluid [3].

Oil lubricant-cooling liquids (LCL) alloyed with additives are used in metal processing as well as in heat exchangers and hydraulic systems. In aqueous **LCLs**, the emulsifying agent envelopes oil particles and prevents their coalescence. Emulsions may be weakly **non-**Newtonian and Newtonian fluids.

References appear at the end of Section 53.8.

5.3.3

Oils

Z. P. Shulman

A. Design relations

Presently, the Predvoditelev-Vargaftik formula [18, 19] is widely used:

$$\lambda = ac_p \tilde{M}_m^{-1/3} \rho^{4/3} \quad (1)$$

where a is the coefficient equal to $4.28 \times 10^{-8} \text{ kg}^{-1/3} \text{ m}^3/\text{s}$ and $\tilde{M}_m$ is the mean molecular mass in kg/mol . As compared to experiment, Eq. (1) gives a mean error as small as 11% at $\tilde{M}_m < 200$, as small as 25% within $200 < \tilde{M}_m < 400$, and 50–70% within $400 < \tilde{M}_m < 600$.

Based on Eq. (1), for $223 < T < 273 \text{ K}$, the following relationship [27] is derived:

$$\lambda = \lambda_{273} \left[1 + \frac{1}{3} \left(\frac{T_{\text{cr}} - T}{T_{\text{cr}} - T_{\text{solid}}} \right)^{1/3} \frac{T - 273}{T_{\text{cr}} - T} \right]^{-4/3} \quad (2)$$

where T_{cr} is the critical temperature and T_{solid} is the solidification temperature. For nine different mineral oils, Eq. (2) gave an error less than 2%.

The empirical formulas for the temperature range $273 < T < 423 \text{ K}$ are presented by Cragoe [20],

$$\lambda = 0.118 \rho_{288 \text{ K}}^{-1} [1 - 0.00054(T - 273)] \quad \text{W/m K} \quad (3)$$

and Smith [21],

$$\lambda = 0.137 \rho_{288 \text{ K}}^{-1} [1 - 0.00054(T - 273)] \quad \text{W/m K} \quad (4)$$

In all the above equations the density is expressed in kg/dm^3 .

Over the temperature range $293 < T < 423 \text{ K}$, specific heat is calculated by the equations of Cragoe [20],

$$c_p = 4200A(\rho^*)^{-1/2} + 3.78(T - 288) \quad \text{J/kg K} \quad (5)$$

and Fortsh and Whitman [22],

$$c_p = [1450 + 3.72(T - 273)](2.1 - \rho^*) \quad \text{J/kg K} \quad (6)$$

Table 1 Oil properties

Material	Name	Country or firm	Temperatures, K	λ_0 (W/m K)	$\alpha_\lambda \text{ K}^{-1}$	$K \times 10^7$, m^2/s	α_k , K^{-1}
Mineral oils	HC-12	U.S.S.R.	293-388	0.130	1.20	0.75	2.53
	tic-20	U.S.S.R.	393-380	0.133	1.26	0.71	1.95
	nrri-38	U.S.S.R.	293-373	0.154	2.99	0.77	2.05
	RAX-50	Olio fiat	293-385	0.136	1.24	0.74	1.33
	EP-50/S	Olio fiat	293-385	0.136	0.45	0.76	1.77
Oils with additives	HC-20+4%PIB 20	U.S.S.R.	293-373	0.129	0.79	0.64	1.76
	HC-20+2%PIB 118	U.S.S.R.	293-373	0.126	0.79	0.59	0.73

From Piku[23].

ρ^+ is the dimensionless density with respect to water at $T = 288$ K. ($A = 0.425$ for paraffin oils; $A = 0.415$ for mixed oils; $A = 0.405$ for naphthenic oils; $A_m = 0.415$.) As compared to experiment, the error obtained by Eqs. (3)-(6) is on the average as small as 15%.

B. Temperature dependencies

According to the available numerous data, at positive (above 0°C) temperatures, $h(T)$, $K(T)$, and $\rho(T)$ are decreasing functions, while $c_p(T)$ is an increasing function. Usually linear approximations are used:

$$a_i = a_{0i} [1 \pm \alpha_i (T - T_0)] \quad (7)$$

a_i is the thermophysical parameter. Indices 0 and i stand for the initial and current temperatures and α_i are constants. In Table 1 the oils most widely used in this country and their foreign analogs are listed.

C. Polymer additives

The apparent viscosity of oils is substantially (by a factor of 10 and more) affected by polymer additives. The investigation of oils thickened with polyisobutylenes (PIB 118, $M_m = 11.8 \times 10^4$; and PIB 20, $M_m = 2 \times 10^4$) (see Table 1) revealed a decrease (up to 20%) in thermal conductivity and thermal diffusivity with increasing molecular weight of the polymer and its content in the oil.

D. Synthetic oils

The properties of synthetic oils [24] studied over the temperature range 303-393 K are presented in Table 5.3.4(1). Note that within the range $213 < T < 303$ K the temperature dependencies become nonlinear. The use of Cragoe's formula, Eq.(3), gives markedly larger errors than in the case of mineral oils.

Nomenclature for Section 5.3.3 appears at the beginning of Part 5. References appear at the end of Section 5.3.8.

5.3.4

Plastic lubricants

Z. P. Shulman

A. Design relations

Plastic lubricants with thickening agents, over the temperature range $293 < T < 413$ K, are governed by the proposed interpolation formulas [25]. For hydrocarbon lubricants,

$$\lambda = \lambda_0 [1 + 0.97C^{1.53} - 0.0057C^{1.18}(T - 273)] \quad (1)$$

$$c_p = c_p [1 + 1.035C^{1.09} - 0.0057C^{1.56}(T - 273)] \quad (2)$$

and for lubricants with soaps and other thickening agents

$$\lambda = \lambda_0 [1 + 4.25C^{1.80} - 0.00157C^{0.57}(T - 273)] \quad (3)$$

$$c_p = c_{p_0} [1 + 80C^{3.13} - 0.012C^{1.98}(T - 273)] \quad (4)$$

where λ_0 and c_{p_0} are the properties of the liquid medium and C is the thickening agent concentration.

Table 2 Anisotropy of thermal conductivity of lubricants'

Lubricant	λ_0	$\lambda_{\perp}$	$\lambda_{\parallel}$	$\lambda_{\parallel}/\lambda_0$	$\lambda_{\perp}/\lambda_0$	$\lambda_{\parallel}/\lambda_{\perp}$
Synthetic Солидол ^b	0.122	0.115	0.153	1.25	0.96	1.33
Lubricant ϕ	0.171	0.153	0.210	1.23	0.89	1.37

Unidirectional orientation is performed by pressing the lubricant through the plane channel with a shear velocity of 300 s^{-1} at $T = 293$ K. Here λ_0 , $\lambda_{\parallel}$, and $\lambda_{\perp}$ are thermal conductivities of the isotropic state, parallel and normal to the orientation axis. From Luikov [26].

^bSolidol.

Equations (1)–(4) correlate the known experimental data with an error less than 5%. The data for plastic lubricants with different kinds of thickening agents are given in Table 1.

Table 1 Lubricant properties'

Material	Name	Country or firm	Temperatures, K	λ , W/m K	$\alpha_{\lambda} \times 10^3$, K^{-1}	c_p , kJ/kg K	$\alpha_{c_p} \times 10^3$, K^{-1}	ρ , kg/m ³	$\alpha_{\rho} \times 10^3$, K^{-1}
Synthetic cooling oils	ХФ-22С-16	U.S.S.R.	303-393	0.160	1.33	1.903	1.64	986.0	0.744
	ФМ-5, 6АП	U.S.S.R.	303-393	0.146	1.51	1.605	0.79	967.1	0.881
	Fuchs	BDR	303-393	0.116	0.89	1.915	1.95	887.7	0.746
Plastic lubricants	Солидол с	U.S.S.R.	293-413	0.148	1.71	2.220	1.40	937.0	0.600
(a) Soap	Униол-1	U.S.S.R.	293-413	0.154	1.38	2.361	1.15	932.0	0.600
(b) Inorganic	Сиол	U.S.S.R.	293-413	0.143	1.39	2.052	1.55	949.0	0.600
(c) Hydrocarbon	I-OH-54rl	U.S.S.R.	293-333	0.143	1.85	2.302	1.43	888.0	0.500

From Tatevosov [24] and Froishteter [25].

B. Anisotropy of thermal conductivity

Platelike, filamentous, needlelike, rodlike and, striplike elements contained in lubricants are oriented in the shear flow. In this case, both the **rheological** and

thermophysical properties of these lubricants substantially are altered. In particular, a **shear-velocity-dependent** anisotropy of thermal conductivity arises. Quantitative estimates are presented in Table 2.

Nomenclature for Section 5.3.4 appears at the beginning of Part 5. References appear at the end of Section 5.3.8.

5.3.5

Lubricant-cooling liquids

Z. P. Shulman

A. Oil lubricant-cooling liquids

The effect of sulfur, chloride, and phosphorus additives on the thermophysical properties of these lubricants is studied in [23,31]. Temperature dependencies are governed by Eq. 5.3.3(7). The additives (up to 20%) are shown to affect inconsiderably (by no more than 12%) thermophysical properties.

B. Aqueous lubricant-cooling liquids

In calculations these are usually considered as binary solutions: water + concentrate (emulsol, synthetic oil,

etc.). The following empirical formulas are known: Fillippov [28] formula is

$$\lambda = \lambda_1 x_1 + \lambda_2 x_2 - 0.72(\lambda_1 - \lambda_2) x_1 x_2 \quad (1)$$

and Missenard [29] formula is

$$\lambda = \lambda_1 \left[1 - z_2 \frac{1 - \lambda_1/\lambda_2}{1 - z_2^{1/3}(1 - \lambda_1/\lambda_2)} \right] \quad (2)$$

Indices 1 and 2 denote water and concentrate (emulsol and oil), respectively; x_1 and x_2 are mass fractions of water and concentrate; z_1 and z_2 are volumetric fractions.

Table 1 Properties of aqueous lubricant-cooled liquids

Number	LCLS (oil, emulsol)	Country or firm	Volumetric content of emulsol (oil), %	λ , W/m K	K , m ² /s
1	UCON H-660	Union Carbide Chemicals	100	0.257-0.261	$(0.91-0.95) \times 10^{-7}$
	UCON H-660 + H ₂ O	Union Carbide Chemicals	0-100	$\lambda = \lambda_{H_2O} \left(\frac{z + 3250}{48z + 3250} \right)$	$K = K_{H_2O} \left(\frac{z + 68.7}{2.1z + 68.7} \right)$
2	Вн-2	U.S.S.R.	100	0.355-0.423	$(0.87497) \times 10^{-7}$
	Вн-2+H ₂ O	U.S.S.R.	0-100	$\lambda = \lambda_{H_2O} \left(\frac{z + 181.8}{2.77z + 181.8} \right)$	$K = K_{H_2O} \left(\frac{z + 45}{1.94z + 45} \right)$
3	HoeS 1/449	BDR	15	0.194-0.184	$(0.87-0.77) \times 10^{-7}$
	HoeS 1/449 + H ₂ O	BDR	0-15	$\lambda = \lambda_{H_2O} \left(\frac{z + 13.1}{1.9z + 13.1} \right)$	$K = K_{H_2O} \left(\frac{z + 15.1}{1.9z + 15.1} \right)$

Temperature range is 293-353 K. From Novichenko [31].

Filippov's formula, Eq(1), gives the smallest error (up to 10%) for oil in water emulsions and synthetic oil solutions.

C. Concentration-temperature dependencies

Empirical formulas are suggested to express the characteristics of lubricant-cooled liquids (**LCLs**) in terms of

the known water properties and volumetric **emulsol** (oil) fractions at a given concentration temperature [31]. These formulas are specified in Table 1. As compared to experiment, the calculation error does not exceed 5.5% for thermal conductivity and 7.2% for thermal diffusivity.

Nomenclature for Section 5.3.5 appears at the beginning of Part 5. References appear at the end of Section 5.3.8.

5.3.6

Polymers

Z. P. Shulman

A. General statements

In this section, the following abbreviations are used: polyvinylacetate (**PVA**), polystyrene (**PS**), polymethylmethacrylate (**PMMA**), polyethylene (**PE**), polyamide (PA), polyvinylchloride (PVC), polypropylene (**PP**), polyisobutylene (**PIB**), and polycarbonate (PC). Polymers form a class of high-molecular compounds with a linear (chain) structure of molecules. The molecular structure may be amorphous (**PS**, **PMMA**, etc.) or more or less ordered (crystalline) (PA, PE, etc.). Polymers may be grouped in three states:

State I: elastorigid (glassy) (**PMMA**, **PS**, PVC)

State II: soft (highly elastic) with large reversible deformation (rubbers and resins)

State III: plastoviscous (viscofluidity) with irreversible stress deformation (noncured resins).

At different temperatures and depending on the rate of deformation, the same polymer can be in each of three states without changing its chemical structure. The boundaries of the states are specified by glass transition temperature T_g and melting temperature T_M . Wide-spread thermoplasts are rigid at room temperature and fluid at high temperatures. These properties simplify the production of workpieces by casting, stamping, and extrusion. The high elastic state is implemented in the intermediate range $T_g < T < T_M$.

The above specific features of polymers substantially affect their thermophysical properties. The data for amorphous polymers can be satisfied with the state equation [32]:

$$\left[-\tilde{R}T \left(\frac{\partial p}{\partial v} \right)_T \right]^{1/2} = (\pi + p) \sqrt{\tilde{M}} \quad (1)$$

Here $v = \rho^{-1}$ is the specific volume, $\tilde{R}$ the universal gas constant, p the pressure, π the internal (van der Waals) pressure, and $\tilde{M}$ the molecular mass of the structural unit of a polymer chain. The values of the constants for several polymers are given in Table 1.

At atmospheric pressure ($\pi \gg p$), the state equation can be simplified to

$$\tilde{M}\pi = \tilde{R} \left(\frac{\partial v}{\partial T} \right)_p^{-1} \quad (2)$$

For slow (equilibrium) expansion $\tilde{M}\pi = 22 \text{ GN/m}^2$ and for very fast (nonequilibrium) expansion $\tilde{M}\pi = 32 \text{ GN/m}^2$ [32]. When $\tilde{M}$ is constant, this implies a sharp increase in the internal pressure at a transition from equilibrium to nonequilibrium conditions.

For compressibility,

$$\beta = -\frac{1}{v} \left(\frac{\partial v}{\partial p} \right)_T = \frac{1}{\rho} \left(\frac{\partial \rho}{\partial p} \right)_T$$

Table 1 State equation parameters^a

Material	$\tilde{M}$, kg/mol	π , N/m	b , dm ³ /kg
PS	104	180	0.822
PMMA	100	210	0.734
Ethylcellulose	60.5	230	0.720
Cellulose			
acetobutyrate	54.4	280	0.688
PE	28.1	320	0.875

From McKelvey [30].

and thermal expansion,

$$\kappa = \frac{1}{v} \left(\frac{\partial v}{\partial T} \right)_p = - \frac{1}{\rho} \left(\frac{\partial \rho}{\partial T} \right)_p$$

the following relationships are suggested:

$$\beta^{-1} = (\pi + p)^2 \left(\frac{\tilde{M}b}{\tilde{R}T} + \frac{1}{\pi + p} \right) \quad (3)$$

$$\kappa^{-1} = (\pi + p) \left(\frac{T}{\pi + p} + \frac{MB}{\tilde{R}} \right) \quad (4)$$

B. Heat capacity

Heat capacity specifies the mobility of the recurring elements of a macromolecule with phase (crystallization, melting) or physical (glassy) transitions. As a rule, glassy polymers obey the linear function $c_p(T)$. A positive jump $\Delta c_p = 11.3\text{--}12.2 \text{ J/mol K}$ is observed near T_g . Empirical relationships $\Delta c_p T_g = 115 \text{ kJ/kg}$ and $\Delta \kappa T_g = 0.113$ [32] are very useful. With crystalline polymer melting, c_p strongly increases and then sharply decreases to a value that still exceeds the heat capacity of the solid polymer. For the melts, the linear relationship is valid:

$$c_p = c_{p,300 \text{ K}} + 2 \cdot \left(11 + \frac{\tilde{M}_s}{\tilde{M}} \right) T \quad (5)$$

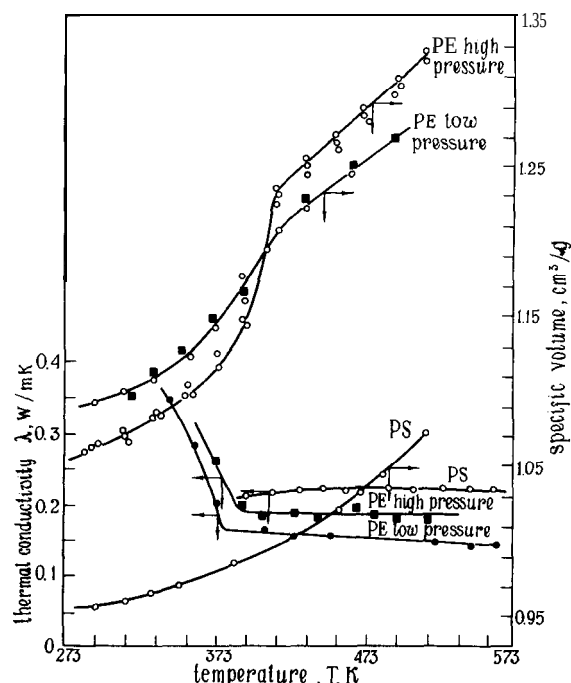


Figure 1 Thermal conductivity and specific volume of some polymers vs. temperature.

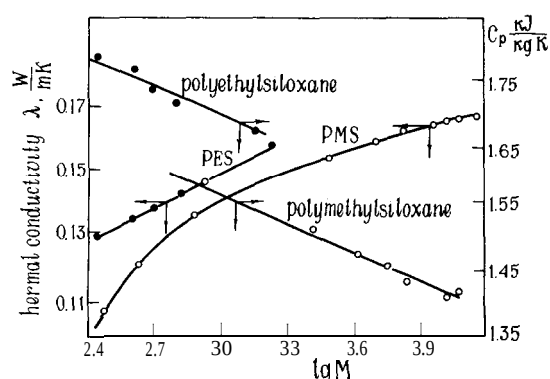


Figure 2 Molecular mass effect on thermophysical properties of polyorganosiloxanes.

$\tilde{M}$ and $\tilde{M}_s$ are the total mass and mass of the side groups of the recurring chain of a macromolecule, respectively.

Thus, the heat capacity of melted polymers with developed side groups (PP, PS, etc.) increases much faster with heating against the linear polymers (PE, PA, etc.). The heat capacity ratio for constant volume and pressure takes the form:

$$c_p - c_v = \frac{T}{\rho} \frac{\kappa^2}{\beta} \quad (6)$$

C. Thermal conductivity

Amorphous polymers are characterized with a smeared maximum near T_g , Fig. 1. The thermal conductivity of crystalline polymers is much higher when in a glassy state than in a highly elastic one. However, according to the relationship from [33], the quantity λ decreases with heating

$$\lambda = A + \frac{B}{T} \quad (7)$$

where A and B are constants. On approaching T_g , λ first sharply decreases and then remains constant or changes slightly with heating.

D. Specific volume v

For amorphous polymers the plot of $v(T)$ [33] is of the form of rounding-off curves. Crystalline polymers in a glassy state obey the linear function $v(T)$ and strong nonlinearity in the melting region beyond which the proportionality $v \sim T$ holds. Specific volume increments are less, the lower the degree of crystallinity or the higher the side group mass, $\tilde{M}_s$.

E. Polyorganosiloxanes

These liquids [34] are widely used as high- and low-temperature heat carriers, coolants, and consistent lubricants having a very low melting temperature (at

-150 K) and a very high boiling point (up to 900 K). Their thermal conductivity linearly decreases with **heat-**ing and rises with increasing molecular mass. The reverse is valid for heat capacity (Fig. 2).

Nomenclature for Section 5.3.6 appears at the beginning of Part 5. References appear at the end of Section 5.3.8.

5.3.7

Oriented polymers

Z. P. Shulman

A. General statements

Polymer materials [34] are widely used as electric, thermal, and cooling insulators or as elements undergoing thermal effects. To estimate correctly the strength, operating and thermal characteristics we need to allow

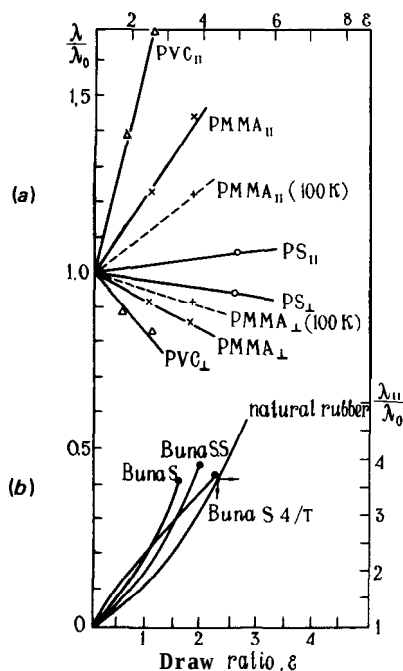


Figure 1 Anisotropic thermal conductivity of some polymers vs. degree of uniaxial draw.

for their dependence on the rheological factor and, in particular, for mechanical history (orientation during production with one or another draw velocity).

The thermal conductivity of oriented polymers is a tensor quantity which is dependent on the strain direction relative to the heat flux vector. Figure 1a illustrates a noticeable increase in $\lambda_{\parallel}$ along the draw axis and a decrease in $\lambda_{\perp}$ in the transverse direction. In semicrystalline polymers, the orientation causes high anisotropy of the thermal conductivity which decreases with lower temperature. Thus, with relative draw $\epsilon = 13$, $\lambda_{\parallel}/\lambda_{\perp} = 10$ for high-density polyethylene, while at $T < 10$ K this ratio is 1.5.

B. Design relations

The relationship between thermal conductivities for isotropic (nondeformed) and oriented states of amorphous material is well governed by

$$3\lambda_0^{-1} = \lambda_{\parallel}^{-1} + 2\lambda_{\perp}^{-1} \quad (1)$$

The reverse proportionality between tensor components of thermal conductivity and linear thermal expansion is also established.

Table 1 comprises experimental and theoretical data for most typical amorphous polymers. Semicrystalline polymers at $T > 30$ K and $\epsilon < 5$ are well described by the modified Maxwell model, Eq. 5.3.1(4). The quality of workpieces, in particular, their strength characteristic,

Table 1 Anisotropy of oriented polymer properties"

Material	Draw degree ϵ , %	Thermal expansion coefficient $\times 10^{-5}, K^{-1}$				Thermal conductivity, W/m K			
		$\kappa_{\parallel}$	$\kappa_{\perp}$	κ_o	κ_o calc	$\lambda_{\parallel}$	$\lambda_{\perp}$	λ_o	λ_o calc
PS	400	7.35	7.98	7.77	7.74	0.173	0.154	0.160	0.163
PMMA	157	5.59	8.58	7.59	7.59	0.238	0.182	0.200	0.197
	275	4.07	9.30	7.56	7.59	0.280	0.168	0.195	0.197
PVC	85	4.45	7.68	6.61	6.63	0.218	0.149	0.168	0.168
	165	2.44	8.63	6.57	6.63	0.279	0.139	0.167	0.168
PC	67	2.31	8.25	6.27	6.25		0.184		0.234

From Novichenok [34].

is markedly improved in the case of film and fiber draw due to molecule orientation. The properties of **manu-**
factures depend on **rheological** conditions: draw velocity,

temperature, and degree of draw. Figure 1b is a plot of the thermal conductivities of eight kinds of vulcanized rubber fibers versus ϵ .

Nomenclature for Section 5.3.7 appears at the beginning of Part 5. References appear at the end of Section 5.3.8.

5.3.8

Effect of external electric and magnetic fields

Z. P. Shulman

■ Suspensions sensitive to external electric and magnetic fields [35] have a wider application in power plant seal systems, nuclear power plants, vacuum devices, heat exchangers, etc. The response of these suspensions to the external field effect exhibits itself in powerful structuring that noticeably changes their rheological and thermophysical properties.

A. Electrorheological disperse systems

These are suspensions of dielectric particles, primarily of silica in nonpolar, weakly electroconducting media. In the electric field, these suspensions sharply and reversely alter the yield stress and apparent viscosity. Most studied are four-component systems containing both the polar activator adsorbed on the particle surface that intensifies structuring and the surfactant that controls suspension consistency.

The growing electric field intensity markedly increases the thermal conductivity of suspensions. With increasing content of the activator there appears a set of stable bridges in these suspensions, and heat transfer occurs primarily along intimately contacting adsorptive shells of particles. Heat conduction along the bridges is enhanced due to decreasing thermal resistance of interparticle contacts [36]. Figure 1 shows the effect of three main factors (particle concentration, activator content, and electric field intensity) on thermal conductivity of a typical aerosil suspension in cetane. It is found that the quantity λ is twice as much as in the electric field. The knee of the curve ($c < 3\%$) is attributed to electric convection. The unique specific

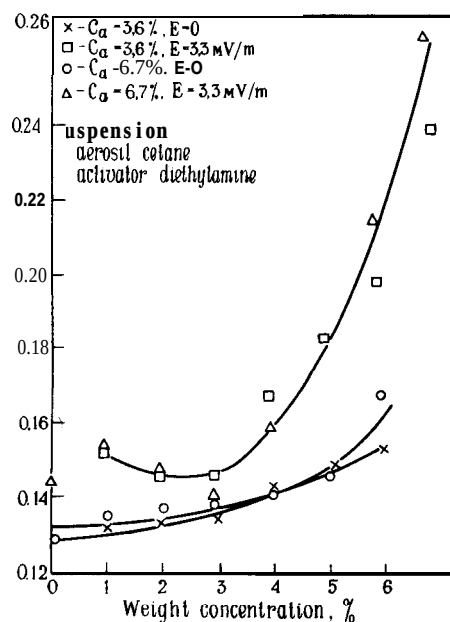


Figure 1 Effect of solid phase and activator content on thermal conductivity of electrorheological suspension.

features of electrorheological suspensions are proposed to be useful in recuperative heat exchangers [37].

B. Magnetorheological suspensions (MRS)

These suspensions are formed by dispersing ferri- and ferromagnetics (magnetite, carbonyl iron, nickel, γ-iron oxide) in highly viscous fluids. Surfactants are added as consistency controllers. The strength of structures is

specified by particle magnetization and interaction in the external magnetic field [38]. **Thermophysical** properties greatly depend on suspension composition, magnitude and orientation of the field. Of special importance is the reciprocal orientation of the magnetic field relative to the heat flux.

In MRS at rest, the anisotropy of thermal conductivity is markedly pronounced, thereby increasing in co-directional thermal and magnetic fields and decreasing in transverse fields (Fig. 2a). This effect is enhanced with growing magnetic field strength and can be related to a contribution to dipole-dipole interaction to the interparticle contact density (Fig. 2b). The data for co-directional thermal and magnetic fields are well correlated in terms of specific particle interaction energy, $e_{dd} = I^2/c$ where I is the MRS magnetization [39] and c is the ferromagnetic concentration.

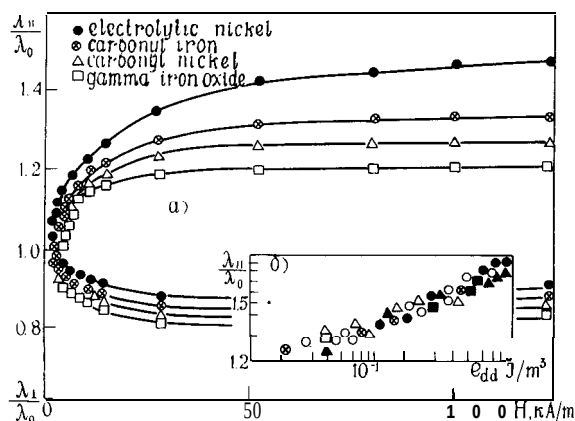


Figure 2 Anisotropy of magnetorheological suspension thermal conductivity on magnetic field.

Simultaneous action of magnetic and shear fields markedly enhances thermal conductivity of **MRS**. The authors of [39] suggest that the shear flow induces cascade disintegration of aggregates. Increasing parallel interparticle couplings substantially increase the instantaneous area of total dynamic contacts, whose thermal resistance is less than the one for a **fixed** layer, thereby intensifying heat transfer primarily in the field direction.

C. Ferrofluids

Ferrofluids [40] show promise for use as high effective heat carriers. A specific temperature dependence of magnetization promotes good mixing even with no gravity forces, since different forces act upon nonuniformly heated liquid volumes from the external magnetic field side. With nonuniform magnetic fields available, the gravity force can be partly or completely compensated under the earth conditions, thus artificially creating one or another degree of imponderability in a nonisothermal medium.

For several **colloids using** magnesite Fe_3O_4 , the following linear relationship is valid:

$$\frac{\lambda}{\lambda_0} = 1 + 3c \frac{\lambda_M - \lambda_0}{\lambda_M + 2\lambda_0} \quad (1)$$

$\lambda_0, \lambda_M = 6.27 \text{ W/m K}$ is the thermal conductivity of the liquid and solid phases and c is the volumetric particle concentration. Up to $c < 18\%$ the quantity λ is independent of the magnetic field intensity within experimental accuracy.

Nomenclature for Section 5.3.8 appears at the beginning of Part 5.

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5.4

Properties of solids

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5.4.0

Introduction

M. Schunck

■ In contrast to the sections on the properties of fluids, this section deals mainly with the materials from which the heat exchangers themselves could be fabricated and only selectively with solid materials that could also be handled in heat exchangers, e.g., pebble heaters. This narrows considerably the range of materials to be treated.

For the more common materials such as metals and alloys, graphite and silicon carbide, refractories and glasses as well as organic polymers, most of the required values are tabulated in the suppliers' catalogs and in the literature. Where such knowledge is lacking (e.g., where the tables do not cover the materials or the temperature range of interest), the problems of predicting physical properties begin.

The solid state is a state of much higher regularity

than that of gases and liquids. Therefore even the prediction of simple properties such as density or thermal conductivity requires the knowledge of other properties—the availability of which is far less probable (e.g., lattice constants of the crystal) than that of the property in question itself.

Methods of predicting physical properties on such a basis are very interesting from a scientific point of view, but they are obviously of no use for the engineer who is in the course of designing heat exchanger equipment. The objective of this section is therefore to provide general rules of material behavior rather than predicting exact values. The calculations in which tabulated or estimated property values may be used are explained in Part 2 of this handbook.

5.4.1

Density of solids

M. Schunck

■ For a material with unknown density (i.e., mass per unit volume, ρ , in kg/m^3) rarely more than the simplest facts will be available. Thus these have to be taken as the basis for deriving an estimated density.

A. Metal alloys

The densities of the pure metals are related to their places in the Periodic table but are not strictly parallel to their atomic masses. The density of alloys can be estimated as the composed density according to the mass fractions of the single elements in the alloy:

$$\rho_A = \frac{1}{x_1/\rho_1 + x_2/\rho_2 + x_3/\rho_3} \quad (1)$$

where ρ_i is the density of the single component and ρ_A the density of the alloy.

However, it has to be noted that the same alloy often can exist in different crystal structures such as face-centered and bodycentered cubic patterns. For the same or nearly same composition, this results not only in slightly different densities but also in largely different coefficients of thermal expansion.

The coefficient of linear thermal expansion (the fraction of elongation caused by the unit of temperature change, α , in m/m K) ranges from 0.02×10^{-4} (Fe + 36% Ni) to 0.26×10^{-4} m/m K (Mg) with most values around 0.1×10^{-4} m/m K . α is generally larger close to the melting point. In alloys, irregularities of the coefficient of thermal expansion are to be expected.

B. Graphite and carbon

The densities of graphite and carbon range from 1 500 to 2 000 kg/m^3 depending upon the degree of regularity and of porosity resulting from the methods of manufacturing. Graphite and carbon can be made impervious by filling the pores with resins. Such an impregnation will increase the density up to about 2 000 kg/m^3 . For heat exchangers serving the temperature range up to 150°C , these are the commonly used materials.

Within certain limitations, the carbonizing or graphitizing process can be repeated after impregnating in order to produce an essentially impervious or even glassy material with a density about equal to that of the normal impregnated material. The coefficient of linear thermal expansion is about

$$\alpha = 10^{-4} a + 0.4 \times 10^{-8} T \quad \text{m/m K} \quad (2)$$

with T in $^\circ\text{C}$ and where $a = 0.01$ for carbon, $a = 0.02$ for impervious carbon, and $a = 0.04$ for pure and impervious graphite.

C. Refractories (oxides and silicon carbide)

Refractories consist mostly of oxides of Al, Si, Mg, Fe, Ti, Cr, Zr, but also of SiC and ZrC. The densities of the pore-free materials vary between about 2 600 kg/m^3 (SiO_2) and 3 700 kg/m^3 (Al_2O_3) to over 4 200 kg/m^3 (40% Cr_2O_3) and 4 700 kg/m^3 (90% ZrO_2). The porosity is normally about 25% and in insulating materials up to 80%.

The mean coefficient of linear thermal expansion is normally in the range 0.05×10^{-4} – 0.08×10^{-4}

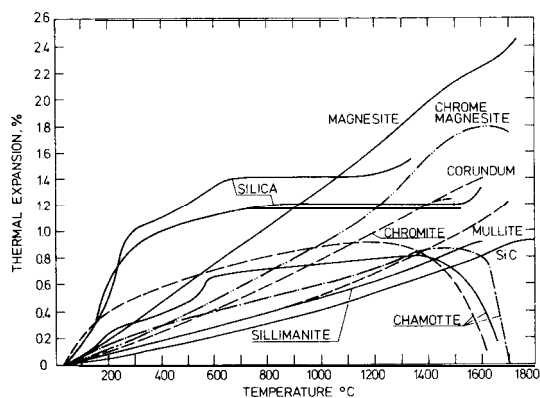


Figure 1 Linear thermal expansion of different refractory materials as a function of temperature [1].

m/m K, but is sometimes about 20% greater in an intermediate temperature range between 300 and 700° C. Refractories containing **MgO** have higher values (0.15×10^{-4} – 0.20×10^{-4} m/m K) while those containing **SiC** have lower values (0.04×10^{-4} m/m K). For illustration, see Fig. 1.

It must be mentioned that leaps (or steps) in the thermal expansion of some materials are observed because of the reversible or permanent changes in the lattice structure of the crystals that occur with high-temperature and low-temperature modifications. **SiO₂** has many modifications with densities between 2 200 and 2 650 kg/m³ (see Fig. 2). Clay brick shows a shrinkage at higher temperatures due to sintering and glassi-

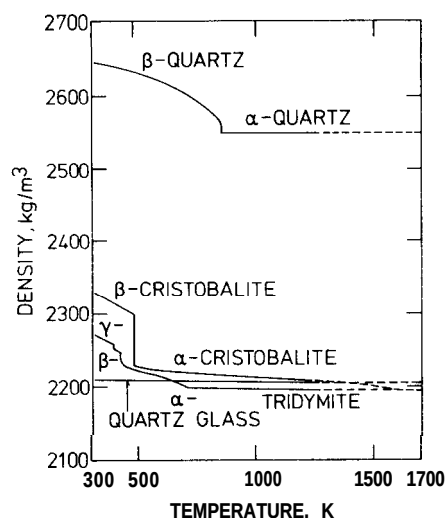


Figure 2 Change of density for different modifications of **SiO₂** during heating, cooling, and transformation processes. Modified from [1].

fyng of the material. This can sometimes be compensated by a sufficient content of **SiO₂** which at the same time will expand.

D. Organics

Organic solids that could be used in the construction of heat exchangers, such as **PTFE**, have densities around 1 100 kg/m³. The coefficient of linear thermal expansion is usually around 1×10^{-4} m/m K.

Nomenclature for Section 5.4.1 appears at the beginning of Part 5. References appear at the end of Section 5.4.4.

5.4.2

Specific heat of solids

M. Schunck

■ Every solid-metallic, nonmetallic, crystalline, or even amorphous-can be considered as a more or less regular three-dimensional lattice of atoms. Each of them is **fixed** in its position by elastic forces that are functions of the atomic distances and the properties of the neighboring atoms. By far the most Important contribution to the internal energy of a solid is the energy stored in the thermal vibration of its atoms in the lattice. These vibrations of an average atom are three dimensional and may be resolved into three independent vibrations parallel to the three coordinate axes.

Similar to the kinetic theory of gases, the kinetic theory of solids assigns to each component the energy

$$\frac{E}{\tilde{L}} = kT \quad \text{joules per average atom}$$

where $\tilde{R}/\tilde{L} = k$ is the Boltzmann atomic constant with the value 1.380×10^{-23} J/K per single atom. (In gases the energy assigned to each degree of freedom is $kT/2$ due to the absence of elastic forces.)

In consequence, a solid with the mass M , containing $\tilde{M}\tilde{L}/\tilde{M}_{\text{at}}$ atoms, should have the internal energy content

$$uM = 3 \frac{\tilde{M}\tilde{L}}{\tilde{M}_{\text{at}}} kT = 3 \frac{MRT}{\tilde{M}_{\text{at}}} \quad \text{J} \quad (1)$$

The internal energy content per unit of atomic mass, u_{at} , is then

$$\tilde{u}_{\text{at}} = uM_{\text{at}} = 3\tilde{R}T \quad (2)$$

At constant volume, all added heat will increase the internal energy, and thus the specific heat at constant volume per unit of atomic mass, $\tilde{c}_{v\text{at}}$, should be

$$\tilde{c}_{v\text{at}} = \left(\frac{\partial \tilde{u}_{\text{at}}}{\partial T} \right)_v = 3\tilde{R} = 24.95 \text{ J/atom K} \quad (3)$$

For calculating c_p from c_v the work of thermal expansion of the solid has to be taken into account:

$$c_p = c_v + \frac{\beta^2 v T}{\kappa} \quad \text{J/kg K} \quad (4)$$

This expression is in analogy with the similar expression for ideal gases:

$$c_p = c_v + P \left(\frac{\partial v}{\partial T} \right)_p \quad (5)$$

where $\partial v / \partial T = \beta v$

P represents $(\beta/\kappa)T$

β is the volumetric thermal expansivity $= 1/v(\partial v / \partial T)_p$ in K^{-1}

κ is the compressibility $= 1/v(\partial v / \partial p)_s$ in m^2/N
 v is the specific volume in m^3/kg

Since it is very unlikely that β and κ are known for a solid with unknown specific heat, this formula can serve to provide a better understanding only. Depending mostly upon the compressibility, the specific heat capacity at constant pressure for most solids is in the range of about 0-15% higher than that at constant volume. This is in good agreement with the Dulong-Petit law, first published in 1819. Dulong and Petit had discovered that the atomic heat of many solids were about the same, with an average value of about $\tilde{c}_{p\text{at}} = 26.7$ J/atom K.

The Dulong-Petit law, simple as it is, applies only in the range above room temperature with exceptions even there. At lower temperature the specific heat of solids decreases rapidly. This is illustrated in Fig. 1 which shows atomic heats at constant volume for some materials in a temperature range from 0 to 400 K.

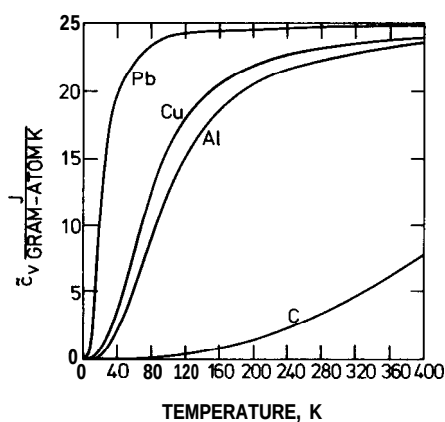


Figure 1 Atomic heats at constant volume as a function of temperature. From Worthing [2].

Improvements in the theory were made by Einstein who introduced Planck's constant $h = 6.625 \times 10^{-34}$ J s and a characteristic frequency ν in s^{-1} , replacing kT in Eq. (1) by the expression $h\nu/(e^{h\nu/kT} - 1)$, which becomes equal to kT in the higher-temperature range but approaches zero together with temperature.

At low temperatures, Einstein's method gave too low specific heats, but its relative success proved that the quantum theory also applies to lattice waves. In consequence, there is a quantum of energy for a lattice wave, now named a **phonon** in analogy to the photon which is the quantum of energy of an electromagnetic wave.

Debye improved Einstein's theory by a more elaborate method. He also employed the quantum value of vibrational energy—the phonon—but as degrees of freedom he defined the possible number of **standing-wave** trains per unit volume and frequency. The theoretical deduction is beyond the scope of this book (see Kittel [3]), however, Debye's theory results in a diagram $\tilde{c}_{v\text{at}}$ versus a dimensionless temperature, T/Θ , with Θ representing the Debye temperature, which is in very good agreement with experimental values of $\tilde{c}_{v\text{at}}$ for various materials. (See Fig. 2.)

There are methods of calculating Θ from other material properties, but the basic values for these will rarely be available. For the present purpose it is therefore recommended that Θ be obtained by the rule

$$\Theta = 3T_{0.7}$$

where $T_{0.7}$ is the temperature where $\tilde{c}_{v\text{at}}$ is 70% of its final value or $\tilde{c}_{v\text{at}} = 17.5$ J/atom K.

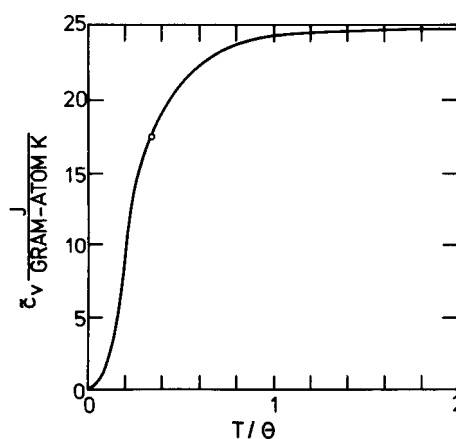


Figure 2 Atomic heat at constant volume, according to Debye's theory, as a function of T/Θ where Θ is the Debye temperature. Simplified from Schroedinger [4].

For low temperatures, approximately up to $T = 0.1 \Theta$ (sometimes only up to $T = 0.02 \Theta$), c_v rises as T^3 (" T^3 law"). The Debye temperatures for some materials are given in Table 1. The rule seems to be valid also for alloys and chemical compounds. Deviations of normally $\pm 10\%$ for c_v and of $\pm 15\%$ for c_p are to be expected, but there are some materials for which the deviations are much greater, e.g., Li.

Debye's theory considers only the most important contribution to the specific heat of solids, that of the lattice vibrations. However, there are many other phenomena that may cause a solid to absorb additional heat, e.g., the changes in modification of a crystal or other changes in the atomic structure (order-disorder phenomena).

Table 1 Debye temperatures Θ for some materials^a

Metal	Θ	Metal	Θ
Pb	88	Al	398
Hg	91	Fe	453
Cd	168	Other	
Na	172	KBr	177
Ag	215	KCl	230
Ca	226	NaCl	281
Zn	235	C	1860
cu	315		

^aFrom Schroedinger [4].

Nomenclature for Section 5.4.2 appears at the beginning of Part 5. References appear at the end of Section 5.4.4.

5.4.3

Thermal conductivity of solids

M. Schunck

■ Thermal conductivity is defined as the ratio of the flux of thermal energy in a given direction to the temperature gradient in the same direction:

$$\lambda = \frac{q}{\partial T / \partial l} \quad \text{W/m K} \quad (1)$$

where $\dot{q}$ is the flux of thermal energy in W/m^2 . This is, of course, also true for a fluid as long as no convective heat transport has to be considered. In a gas, the kinetic theory of gases provides an easy explanation for the thermal conductivity λ , relating it to the heat capacity per unit volume of the gas c_p , the average particle velocity v , and the mean free path l :

$$\lambda = \frac{1}{3} c_p v l \quad (2)$$

In solids, as in gases and liquids, the thermal energy is mainly stored in the **motional** energy of the atoms, but in solids they are **fixed** to their respective positions within the lattice by elastic forces. Explaining thermal conductivity is therefore explaining the different kinds of interaction by which the lattice vibrations are transmitted throughout a crystalline or amorphous solid when the equilibrium is distorted by a temperature gradient.

At moderate temperatures, i.e., up to about 1 000 K, there are mainly two possible vehicles for the transport of heat through a solid body:

1. The elastic forces in the lattice which cause the atoms to arrange their vibrations in trains of standing waves. The quantum of energy of such a standing wave is called a phonon. Since an otherwise undisturbed lattice wave travels through a regular lattice without

change of momentum, the phonons can be treated much like particles.

2. Free electrons which as electron gas circulate between the atoms, picking up energy in **collisions** with vibrating atoms and delivering energy to other vibrating atoms. Free electrons are present in electric conductors (metals, graphite, silicon carbide) and, to some degree, in semiconductors.

In the temperature range above about 1 000 K, enough photons are stimulated to take part in the transport of heat, especially in materials transparent to infrared radiation. The photons are also to be considered as particles, and the contribution of each of the three types of carriers to the thermal conductivity would then be

$$\lambda_i = \frac{1}{3} c_i v_i l_i \quad (3)$$

Since there are no elementary means of calculating the mean free path l for the different types of carriers, the above relationship can be used in a very general way only.

For further discussion, the solid materials will be divided into electrical conductors, electrical nonconductors or insulators, and semiconductors.

A. Thermal conductivity of electrical insulators

In electrical insulators (e.g., refractory materials such as SiO_2 , Al_2O_3 , etc.) up to about 1 000 K, phonons are the only carriers of thermal energy. At low temperatures (say below 30 K) they are nearly independent of each other. This means that their average free path is **only** limited by irregularities of the crystalline structure. In

a high-purity single crystal the mean free path in this temperature range can reach a few millimeters, but even the presence of different isotopes can scatter the **pho**ns or limit their free path.

As long as the mean free path of the phonons is a function of the configuration of the crystal, l can be considered a constant. The velocity of sound, v , is essentially independent of temperature, and thus the conductivity

$$\lambda = \frac{1}{3}cvl$$

will vary with the specific heat c , which in this range varies as T^3 according to **Debye's** theory. More-regular crystals will show higher values of A than less-regular ones, and in glasses λ will be much lower than in any crystal.

With increasing temperature the mean free path of the phonons will be limited more and more by collisions with other phonons. These interactions between **pho**ns and phonons, according to Peierls [5] can be classified as normal processes (which do not give rise to thermal resistance) and Umklapp (reversing) processes in which momentum is lost. The probability of the occurrence of Umklapp processes rises as T , thus decreasing the mean free path and the thermal conductivity as T^{-1} .

With increasing importance of phonon-phonon interactions at higher temperatures, the effect of crystal regularity on the thermal conductivity decreases. At about 1 000 K the thermal conductivity of a very regular crystal and of a glass are in the same order of magnitude. On the other hand, the very disordered crystal structure of a glass will result in comparatively very short mean free paths even at low temperatures, and in a wide range of temperature λ will therefore vary as c , i.e., increase approximately according to **Debye's** theory (see Sec. 5.4.2).

At temperatures of about 1 000 K the thermal conductivity of ceramic materials in their nonporous body is in the order of magnitude of 2 W/m K, glasses generally somewhat lower. Apparently the lighter elements in the compounds are more favorable to a high thermal conductivity than the heavier ones.

At temperatures above 1 700 K the transport of heat due to internal radiation becomes important, especially in refractories containing a large amount of glassy matter. The thermal conductivities of some nonporous refractory materials are shown in Fig. 1.

Very often the thermal conductivity of refractory material is reduced by a certain degree of porosity—the effect of which is mainly determined by the distribution and shape of the pores in the solid body and by the thermal conductivity of the gas in the pores. As a rough rule, a 1% increase in porosity will increase the thermal resistance (A^{-1}) by about 5%. This rule is valid up to a porosity of about 60%, and for a temperature up to

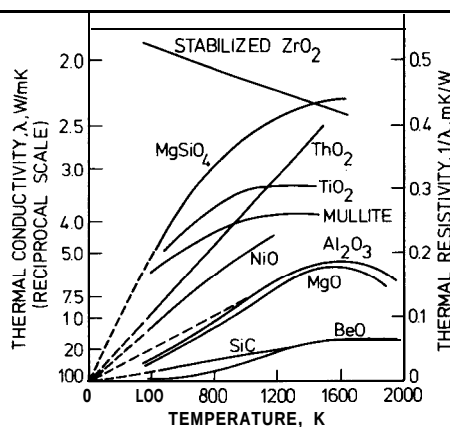


Figure 1 Thermal conductivities of some (nonporous) oxitic materials as functions of temperature. From Kingery [6].

about 1 200 K. At higher temperatures the radiative heat transfer through the pores becomes important, contributing an apparent thermal conductivity that varies as T^3 . At temperatures above 1 700 K an increase in porosity will therefore cause an increase of thermal conductivity.

Hydrogen and helium have much greater thermal conductivities than all other gases. Their presence in the pores will therefore markedly increase the thermal conductivity of a porous refractory material. The effect of gas convection in the pores increases with the size of the single pore and with the pressure of the gas. It **should** also be noted that any condensation and vaporization within the pores of an otherwise insulating material **will** considerably contribute to the transmission of heat.

B. Thermal conductivity of electrical conductors

In metal lattices, the valence electrons can circulate more or less freely among the atoms, thus being able to transmit electric charge, i.e., to produce electrical conductivity. Their mean free path is limited at very low temperatures mainly by impurities and irregularities of the lattice. At higher temperatures the interactions between electrons and vibrations of the **atoms**—phonons—also become more and more important. In very pure crystals, this effect begins at very low temperatures. Metal alloys, due to their less-regular lattice, show a much lower electrical conductivity at low temperatures than pure metals do. So the decrease due to electron-phonon interactions becomes obvious in a higher temperature range only. The change of electrical conductivity between room temperature and the temperature of liquid helium (4 K) can vary between about a factor of 10 000 for very pure metals and 2 in specific **alloys**.

By their ability to interact with lattice vibrations, the free electrons will pick up energy from vibrating atoms and transmit it to other atoms, thus increasing

their vibrational energy. On the average, this results in a transmission of heat in the direction of the negative temperature gradient. Due to the relatively high velocity of the electrons and their relatively large mean free path, their contribution to the thermal conductivity is normally much higher (5-50 times) than that of the **phonons**, in spite of their very small contribution to the specific heat.

The exchange of energy between phonons and electrons is subject to quantum effects which allow the number of electrons participating in the exchange of energy with phonons increase as T . Even at room temperature only about 1% of the free electrons of a metal are engaged in the transport of heat. Therefore, at very low temperatures (up to 15 or 30 K) where the electron free path is only limited by lattice imperfections, the **thermal conductivity** of metals varies as temperature, whereas in the same temperature range the **electrical conductivity** varies as T^{-5} . The state of electrical superconductivity is not accompanied, for a similar reason, by an infinite thermal conductivity because the fraction of electrons participating in the superconduction no longer contributes to the thermal conductivity.

At higher temperatures the number of electrons contributing to the transport of thermal energy continues to rise as T , but at the same time their mean free path decreases by phonon-electron interactions. The first phenomenon will dominate over the whole temperature range in metals that start out with a high density of lattice imperfections, thus resulting in a permanent rise of thermal conductivity with increasing temperature. On the contrary, in pure metals the thermal conductivity reaches a maximum at the temperature of commencement of phonon-electron interactions followed by a decrease of thermal conductivity over the rest of the temperature range (see Sec. 5.5.6). For temperatures over about 150 K the thermal conductivity λ and the electrical conductivity σ are related to each other by the Wiedemann-Franz-Lorenz law

$$\frac{\lambda}{T} = L\sigma \quad (4)$$

where L is the Lorenz number = $2.45 \times 10^{-8} \text{ W } \Omega/\text{K}^2$ from theoretical considerations. Practical values of L range between 2.3×10^{-8} and $3.2 \times 10^{-8} \text{ W } \Omega/\text{K}^2$.

The fact that λ/T and not λ must be compared with σ is explained by the temperature dependency of the fraction of electrons participating in the energy ex-

Table 1 Experimental values^a of the Lorenz number $L = \lambda/(\sigma T)$

Metal	Temperature (K)	$L \times 10^8$
Al	21.2	1.77
	313.2	2.23
Mo	90.2	1.16
	213.2	2.61
W	90.2	2.00
	213.2	3.06
Fe	90.2	1.60
	213.2	2.47
Pt	20.1	1.09
	213.2	2.51
Cu	21.2	0.77
	83.2	1.57
	273.2	
Ag	90.2	1.62
	213.2	2.31
Au	21.2	1.85
	83.2	2.05
	213.2	2.35
Pb	21.8	1.48
	291.2	2.45

^aFrom D'Ans and Lax [7].

change with phonons. Some values of L are tabulated in Table 1.

C. Thermal conductivity of electrical semiconductors

Electrical semiconductors take an intermediate position between metals and insulators. Thus their thermal conductivity can be estimated as the sum of their lattice conductivity λ_l and their electron conductivity λ_e . The latter can be calculated by the **Wiedemann-Franz-Lorenz law**:

$$\lambda = \lambda_l + \lambda_e = \lambda_l + L\sigma T \quad (5)$$

with $L = 2.45 \times 10^{-8} \text{ W } \Omega/\text{K}^2$.

It should be added that there is an additional effect in semiconductors which can also contribute to the thermal conductivity: bipolar diffusion. At sufficiently high temperatures (above room temperature, but markedly only over 800 K) an increasing number of electron-hole pairs can be thermally generated. These pairs will recombine on the average at places of lower temperature, thus delivering their energy of generation.

Nomenclature for Section 5.4.3 appears at the beginning of Part 5. References appear at the end of Section 5.4.4.

5.4.4

Emissivity of solids

M. Schunck

A. General introduction

Within the limits of **Planck's** quantum theory, any kind of energy input to an atom or molecule can cause one or more of its electrons to rise to a higher-energy state. In returning to a lower state the electron **will** emit a photon-the quantum of electromagnetic radiation-the energy of which is

$$E_q = h\nu \quad \text{J} \quad (1)$$

where h is Planck's quantum constant = 6.62×10^{-34} J s and ν the frequency of the electromagnetic wave in s^{-1} .

As long as only single atoms are considered there are a limited number of discrete states of energy, the differences of which correspond with the frequencies of the photons that can be emitted or absorbed. These frequencies or spectral lines are characteristic for the kind of atom in question.

It is also possible that a photon is absorbed with a higher frequency than the highest frequency corresponding to the differences in the energy levels of the atom. In such a case an electron will leave the atom, becoming a free electron; the atom is therefore ionized. Vice versa recombination of a cation with an electron may give rise to the emission of a photon of higher frequency. This kind of emission has a continuous spectrum of frequencies. Low-frequency (infrared) photons can also be emitted or absorbed by vibrations or rotations of dipole molecules, thus creating emission or absorption bands.

In solids, there is a great variety of additional interaction effects which tend to widen the spectral

lines, make them overlap, and thus produce a more or less continuous spectrum of radiation frequencies. The ideal emitter of thermal radiation-the black body-has a completely continuous spectrum. It is ideal since there is no other body or surface which at a given temperature will emit more radiative energy in any range of frequencies than the black body. The name black body originates from the fact that surfaces covered with platinum black or with lamp black come very close to the ideal emitter. White frost is also very black, except in the visible range of wavelengths.

From experimental work and theoretical considerations Stefan in 1879 and Boltzmann in 1884 concluded that the total rate of emission from a black body is proportional to the fourth power of its absolute temperature :

$$\dot{q}_b = \sigma T^4 \quad \text{W/m}^2 \quad (2)$$

Where σ is the **Stefan-Boltzmann** constant, $5.67 \times 10^{-8} \text{ W/m}^2 \text{ K}$.

Planck's efforts to find an explanation for the distribution of energy over frequency observed in the spectrum of a black body resulted in the quantum theory presented in 1900. He derived the following theoretical equation for the monochromatic emissive power of a black body as a function of wavelength:

$$E_{\lambda b} = \frac{2c^2 h}{\lambda^5} \frac{1}{e^{ch/k_B \lambda T} - 1} \quad \text{W/m}^3 \quad (3)$$

where $E_{\lambda b}$ is the emissive power per unit of radiating surface and wavelength

c is the velocity of light in **vacuo**, $2.998 \times 10^8 \text{ m/s}$

h is Planck's quantum constant, 6.62×10^{-34}

J s

k_B is the Boltzmann constant, 1.384×10^{-23}
J/K

T is the temperature of the radiating surface,
in K

λ is wavelength = c/ν , in m

Figure 1 has been obtained by solving the above equation for several temperatures. It also illustrates Wien's displacement law developed in 1893. According to this law the wavelength λ_m with the maximum monochromatic emissive power is proportional to T^{-1} , or $\lambda_m T = \text{const.}$ It must, however, be emphasized that Wien's displacement law is only valid for black and gray radiators. There is no real surface that reaches 100% of the theoretical black body radiation. Stefan had used a surface covered with platinum black, but later it was found that a hollow enclosure, externally insulated and heated to a constant and equal temperature must act like a nearly ideal black body if thermal radiation escapes through a comparatively small peep-hole.

Since the curves in Fig. 1 show the absolute maximum possible thermal radiation at each temperature and wavelength, they give the emissive power of a surface with the emissivity of 1 (or 100%), where the emissivity is defined as the ratio of emissive power of a real surface to that of the black body. The emissivity of real surface is in all cases less than 1. If it is the same (say 0.6 or 60%) for all wavelengths and for all directions of space, then the surface is called a gray surface, even if this property is only present in a certain temperature range.

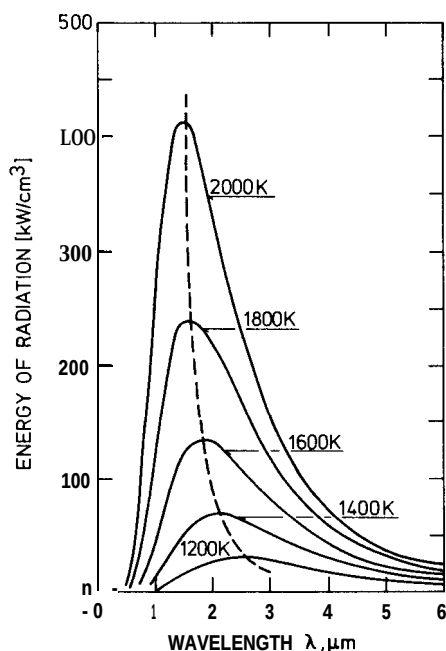


Figure 1 Monochromatic emissive power of a black body radiator as a function of wavelength.

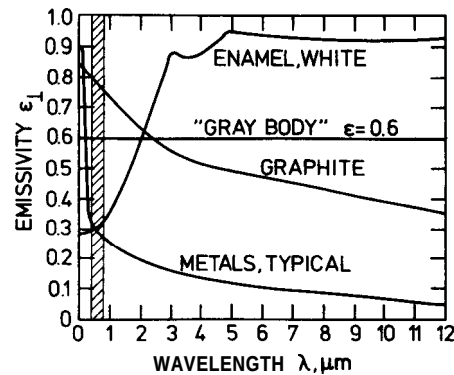


Figure 2 Typical data for the variation of monochromatic emissivity with wavelength.

For many technical purposes, surfaces can be treated as gray **with** a sufficient accuracy. But most surfaces deviate differently for different wavelengths due to resonance effects similar to the radiation bands of a gas, and also the emissivity will vary depending upon the angle of radiation. Hence it is sometimes necessary to **define** (a) **total** emissivity (all directions, all wavelengths), (b) **normal** total emissivity (all wavelengths but direction **only** normal to the surface), and (c) monochromatic or **spectral** emissivity (ϵ_λ for a given wavelength). Figure 2 shows typical data for the variation of monochromatic emissivity with wavelength.

The total emissive power per unit area of a surface is therefore

$$E = \int_{\lambda=0}^{\lambda=\infty} \epsilon_\lambda E_{\lambda b} d\lambda \quad \text{W/m}^2 \quad (4)$$

The interactions between thermal vibrations and photons are independent of the direction of energy transfer, i.e., any process that can emit an electromagnetic wave can also be reversed by absorbing the same kind of wave. Therefore, all radiation impinging on a black body **will** be absorbed by it. Real surfaces, however, will absorb only a part of the radiation and reflect the rest of it, the ratio between absorbed energy E_a and total impinging energy E_t being defined as absorptivity $\alpha = E_a/E_t$.

In 1860, Kirchhoff established the law that **emissivity** ϵ and **absorptivity** α at the conditions of thermal equilibrium must be equal for any kind of surface. This law not **only** illustrates the reversibility of the process creating or absorbing radiation, but also follows from the condition that a particle inside an isothermal radiating enclosure cannot be heated by radiation to a temperature above that of the enclosure. Once the temperatures are equal the particle must lose as much energy by radiation as it gains by absorption. Kirchhoff's law applies not only to total emissivity and absorptivity but also to the values at given frequency and/or direction.

The process of absorbing and emitting radiation takes place in a more or less extended layer of matter beneath the surface of a body. According to the Lambert-Bouguer law, layers of equal thickness will absorb equal fractions or percentages of the impinging radiation. By definition, the fractional reduction of the radiative energy transmitted through a layer of matter with a thickness of one wavelength λ_m (measured in the material) is $e^{-4\pi\kappa}$, where κ is the absorption index. Materials with large values of κ absorb the radiation in very thin layers; those with extremely low values of κ may even be transparent.

Large values of the absorption index κ do not go along with high absorptivities (α) or emissivities (ϵ), however. On the contrary, if all transmitted radiation is absorbed in a very thin layer near the surface, then most of the impinging radiation **will** not be absorbed at all but will be reflected. This statement may appear to be contradictory, but it applies to all kinds of waves and can be verified most easily with mechanical models.

In 1860, **Lambert** stated that the rate of emission from a radiating surface often varies as $\cos \vartheta$ if ϑ is the angle of emission, i.e., the angle between the normal to the radiating surface and the considered pencil of radiation. If the radiating surface is thought of as the plane of a hole in a radiating hollow enclosure, then Lambert's cosine law is immediately obvious, since the projection of the radiating surface on a plane perpendicular to the direction of radiation will decrease as $\cos \vartheta$. Thus a radiating piece of tube of uniform temperature with a surface obeying the **Lambert** cosine law would look like a radiating rectangle or slot. For illustration see Fig. 3.

In other words, Lambert's cosine law states that the rate of radiation from a surface in a given direction per unit of the solid angle and per unit of the *projection* of the surface on a plane normal to the pencil of radiation (instead of the unit area of the surface itself) is a constant. It is defined as the intensity of radiation, and with this definition the polar diagram for the distribu-

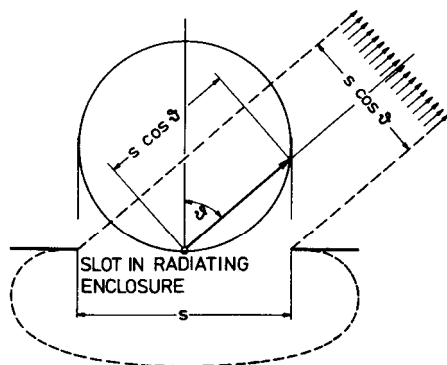


Figure 3 Demonstration of Lambert's cosine law with the conditions at a radiating slot.

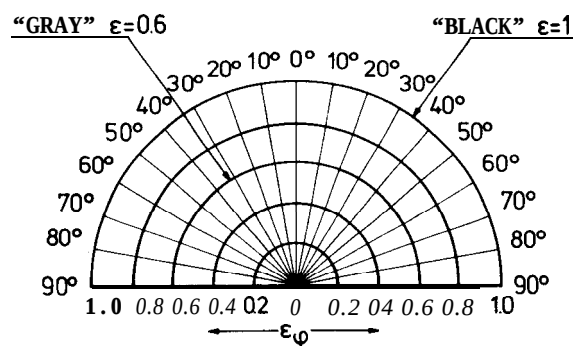


Figure 4 Directional distribution of the emissivity of gray and black **Lambert** radiators.

tion of intensity over the angle of radiation is a semicircle for a **Lambert** radiator.

With the intensity of black body radiation at a given temperature taken as unity, the directional distribution of the emissivities of all real surfaces must be curves within this semicircle where gray **Lambert** radiators are represented by parallel semicircles. See Fig. 4. The intensity of radiation defined above will also not change with distance, since the unit of the solid angle is independent of distance. However, the definition applies also if the solid angle is subtended at the observer's eye. In this case, the solid angle decreases reciprocal to the square of the distance in the same way as the flux of radiation, and the ratio of flux to solid angle again remains constant. This explains the fact that two equal radiators of equal temperature but in different distances appear to the observer as equal in color and brightness. The same is true for all optical images of a radiator which could be produced with lenses or mirrors.

For the radiation impinging on a partially reflecting surface (e.g., a gray one), the directional distribution of the reflected fraction can vary depending upon the structure of the surface. If the roughness is very small the surface will be a specular reflector. With increasing roughness the reflected radiation will become more and more diffuse but will **still** have a specular component. **This** will apply as long as the surface irregularities have small slopes such that in large measure the reflected beams do not hit the surface again. With increasing slopes, the surface irregularities convert into cavities where multiple reflections can take place. This leads to a higher absorptivity and, in consequence, to a higher emissivity of the surface.

B. Emissivity of metals-electrical conductors

As a result mainly of the strong interactions between photons and free electrons, the infrared absorption index of electrical conductors is very high; i.e., only a very thin layer under the surface of a conducting body participates in the exchange of radiation with the surroundings. Accordingly, the reflectivity is high, and the

emissivity (which is equal to the absorptivity) is low. (The high absorption index goes along with low absorptivity, see above.)

For wavelengths over $3\text{ }\mu\text{m}$ ($3 \times 10^{-6}\text{ m}$), the monochromatic emissivity values are generally lower than 0.2 and decrease with increasing wavelength. In the visible range and in the near infrared the relationships become quite complicated. Many metals show a sudden rise of emissivity/absorptivity much like absorption bands in fluids. In this range, no simple and reliable rules for estimating the emissivity exist, except for judging the appearance in regard to its reflectivity $\rho = 1 - \epsilon = 1 - \alpha$.

Typical emissivities are:

polished silver	0.02
polished aluminum	0.05
polished iron	0.1
bright cast iron	0.2
aluminum paint	0.3

Up to temperatures of about 900 K, where essentially no radiation in the visible range is emitted, the total normal emissivity of metals, ϵ_1 , can be related to the specific electrical resistivity, ρ_0 , by the following equation:

$$\epsilon_1 = 0.35T\rho_0^{0.5} \quad (5)$$

with T in kelvin and ρ_0 in $\Omega\text{ m}$.

Since only the layer immediately below the physical surface emits and absorbs radiation, the surface conditions have a great influence on the radiative properties of electrical conductors. Even very thin oxide layers change the visual appearance of surfaces, and thus affect the emissivity/absorptivity. They generally give rise to a higher emissivity.

Since the emissivity/absorptivity is related to wavelength, the total absorptivity depends on the spectral distribution of the impinging radiation, being greater for shorter wavelengths, i.e., for higher temperatures of the radiation emitter. The total normal absorptivity $\alpha_1(T_{e,b}, T_{a,m})$ of an electrical conductor at temperature $T_{a,m}$ absorbing radiation from a black emitter at temperature $T_{e,b}$ is often calculated at the geometric mean temperature T_{gm} given by:

$$T_{gm} = (T_{e,b} \times T_{a,m})^{0.5} \quad (6)$$

The directional distribution of the emissivity/absorptivity of metals and electrical conductors deviates strongly from that of a Lambert radiator since the emissivity is small in the normal direction but increases rapidly with increasing angle of radiation, ϑ , for ϑ values greater than 40° . This effect goes along with increasing polarization of the emitted radiation. At an angle ϑ

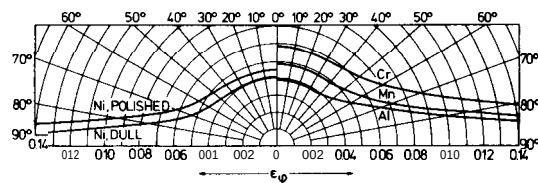


Figure 5 Directional distribution of the emissivity/absorptivity of metallic radiators. From Schmidt [8].

close to 90° , one could thus expect an emissivity of about $\epsilon = 0.5$. See Fig. 5.

Therefore, the reflectivity $p = 1 - \epsilon = 1 - \alpha$ of a metal decreases with increasing angle of incidence, and it is the difference in the directional distribution of the reflectivity which enables us to see a difference, even in diffuse illumination, between a rod of polished metal and a rod painted white.

Very thin layers or sheets of metal (thickness on the order of magnitude of one wavelength) show a marked decrease in reflectivity, caused by a decrease in the absorption index. In consequence, they begin to become transparent at much larger thicknesses than could be expected in regard to their absorption index observed otherwise.

C. Emissivity of electrical nonconductors

Because of a lack of free electrons, electrically nonconducting materials have low absorption indexes κ (see Sec. A). The interaction between thermal vibrations and radiation is mostly effected by electric dipoles unless, at higher frequencies (i.e., shorter wavelengths) electrons in the atoms can be stimulated. Accordingly, these materials have large emissivities in the infrared above $\lambda = 2\text{--}3\text{ }\mu\text{m}$ [$(2\text{--}3) \times 10^{-6}\text{ m}$], sometimes only above $\lambda = 10\text{ }\mu\text{m}$ (MgO). See Fig. 6.

Ion crystals like NaCl show optically active vibrations of the anion lattice and the cation lattice relative to each other in the medium and far infrared. These cause bands of metallic reflectivity in the respective frequency ranges. Oxides also show marked bands of

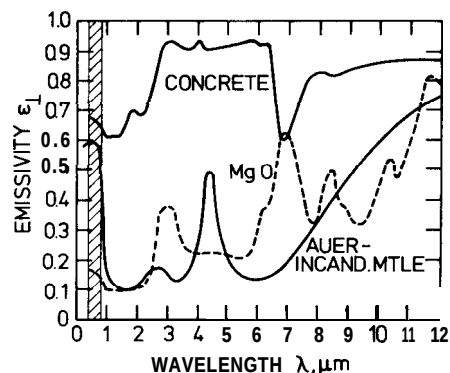


Figure 6 Monochromatic normal emissivity of electrical nonconductors as a function of wavelength. From Sieber [9].

reflectivity in the near infrared for the dual-atom light oxides MgO , CaO , and BaO . For the heavier molecules, such as Al_2O_3 , these bands are in the medium and far infrared and are thus much less important for thermal radiation.

In the visible range, and in the near infrared, the emissivities of insulators vary widely (like that of metals) and can best be estimated from their visual appearance. The radiative properties of insulators are also dependent of temperature. The electron levels are all fully occupied and therefore unable to absorb or emit energy at normal temperatures. At sufficiently high temperatures, however, the electrons are stimulated to jump to higher energy levels, thus providing an electron gas (i.e., free electrons) that has the ability to emit and absorb radiation with a continuous spectrum in the visible and ultraviolet range.

Generally, with increasing temperature the absorption/emission bands of oxides become wider, and their maxima change to longer wavelengths. Many of them do not show a red or yellow heat when they are heated up, but not too far from the melting point they begin to emit a nearly white radiation with an intensity not much inferior to that of a black body.

A similar effect is known from the Auer incandescent mantle for gas lighting. This mixture of thorium oxide and cerium oxide has a very small emissivity in the infrared but a large one in the visible range. Thus, at a given heat input, it does not lose much energy by infrared radiation and therefore reaches a higher temperature with accordingly higher emission in the visible range. Even small contents of the dark oxide Fe_2O_3 in light oxides such as Al_2O_3 will increase the emissivity/absorptivity considerably.

If a surface receives radiation from a source of higher temperature, the transmitted energy depends on the monochromatic absorptivity of the colder surface and on the monochromatic emissivity of the source. If the source is a black radiator and the receiving surface is at a constant temperature, then an apparent absorptivity of the surface for radiation of varying temperature can be given. See Fig. 7.

Of course, the receiving surface also emits radiation corresponding with its temperature and monochromatic emissivity. This is one reason why tanks are often painted white: the white paint has a low emissivity/absorptivity in the visible range of wavelengths, where the maximum energy is transmitted from the sun. But in the infrared, the white paint is nearly equivalent to a black radiator and is therefore able to emit a maximum of energy in the range of wavelengths typical for its actual temperature. Thus, the heating up of a tank due to sunshine is minimized.

The directional distribution of the emissivity/absorptivity of insulators is very different from that of conductors, being much more like that of a Lambert

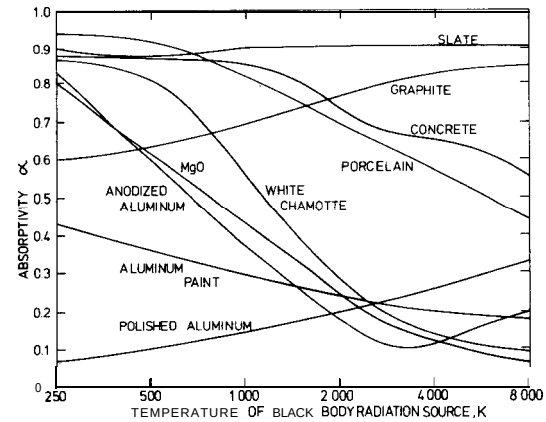


Figure 7 Effect of the temperature of a (black body) source of radiation on the absorptivity of various surfaces at ambient temperature. From Sieber [9].

radiator. Again, however, the effect of polarization causes a decrease to zero of the emissivity for angles of emission approaching 90° . See Fig. 8. As the figure indicates, the ratio between total and normal emissivity, ϵ_t/ϵ_n , is in the range 0.93–0.98.

In transparent matter, e.g., glasses, the impinging radiation is partially reflected, partially transmitted, and partially absorbed. The absorption is then defined by the Lambert-Bouguer absorption index κ (see Sec. A) or by the Lambert-Beer absorption coefficient $\bar{\alpha}$ which is defined by

$$E(x) = E(0)e^{-\bar{\alpha}x} \quad (7)$$

where $E(0)$ is the energy of radiation entering the surface ($x = 0$) unreflected, and x is the coordinate of thickness in the penetrated layer. $\bar{\alpha}$ is usually given in cm^{-1} , and it is related to $\kappa(\lambda)$ for a given wavelength λ by

$$\bar{\alpha} = \frac{4\pi\kappa}{\lambda} \quad (8)$$

(If $\bar{\alpha}$ is given in cm^{-1} , then λ must be given in cm also.) In Fig. 9 an example is shown. A value of $\bar{\alpha} = 0.1$ means

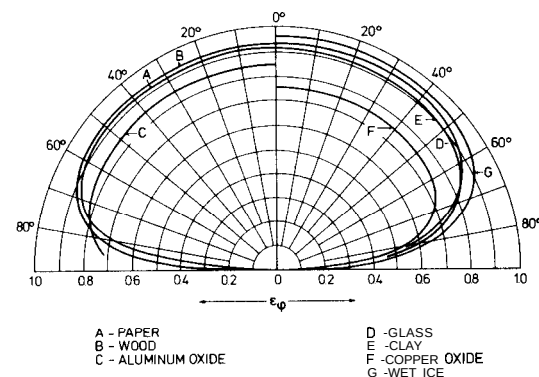


Figure 8 Directional distribution of the emissivity/absorptivity of electrically nonconducting radiators. From Schmidt [8].

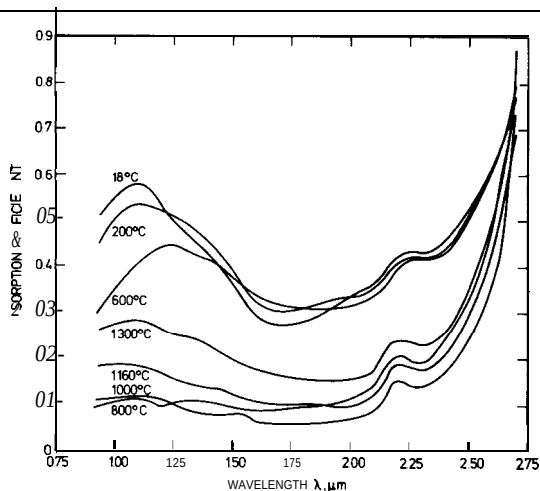


Figure 9 Monochromatic absorption of window glass as functions of wavelength at different temperatures. From Pepperhoff [10].

that a sheet of window glass with a thickness of in. = 0.635 cm will transmit 93.8% of the entering radiation.

D. Emissivity of scattering absorbing materials

In refractories and similar materials, the emissivity is not only a function of the kind of material but also of the grain size, this influence being more important in materials with larger values of emissivity. See Fig. 10. Proceeding from a transparent, single crystal to a material with finer and finer grain, first the emissivity/absorptivity increases with decreasing transparency. Next, as the grain becomes still finer, the reflectivity will increase with the emissivity/absorptivity now decreasing accordingly. In other words, the Lambert-Bouguer absorption index κ increases with the internal surface area.

In the light oxides (MgO , Al_2O_3), the grain size is also important for the influence of temperature on emissivity—the influence being greater with larger grain size and vanishing at grain sizes below about $3\ \mu\text{m}$.

If single particles are suspended in a gas or in a transparent medium, then the impinging radiation will be scattered and lose energy with much the same effect as by absorption. The Lambert-Beer absorption coefficient can then be replaced by an extinction coefficient τ . The decrease of the radiation in its original direction will then be

$$\frac{dE}{dx} = -E\tau \quad (9)$$

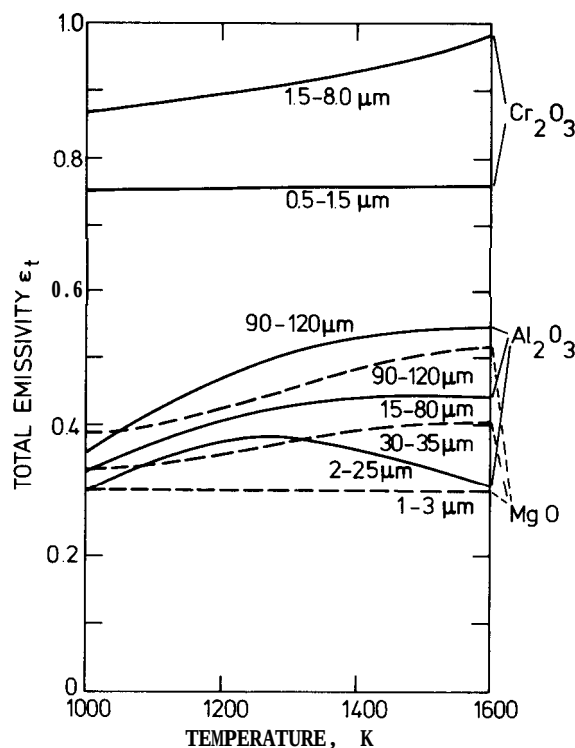


Figure 10 Influence of temperature and grain size on the total emissivity of refractory materials. From Pepperhoff [10].

or

$$E(x) = E(0)e^{-\tau x} \quad (10)$$

As long as the center-to-center distances between the particles are more than 3-4 radii, the extinction coefficient τ is determined by the sum of the individual particle contributions.

For particle diameters larger than about two wavelengths, the single particles act as independent emitters/absorbers with the sum of their cross sections per unit volume. Very small particles with diameters below one-quarter of a wavelength will cause an extinction coefficient that is proportional to the total particle volume per unit volume and inversely proportional to wavelength.

If a surface is covered with pigments, the shape of the pigment particles must be considered. Flat-pigment particles are in most cases oriented parallel to the surface during the process of application or curing of the coating. This phenomenon can greatly increase the reflectivity if the pigment is reflecting, and vice versa.

Nomenclature for Section 5.4.4 appears at the beginning of Part 5.

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5.4.5

Elastic properties

S. F. Pugh

A. Introduction

Solids deform when subjected to stresses. The strain is defined as the degree of distortion per unit length, e.g., the change in length per unit length of a wire when subjected to a tensile stress. The stress is defined as the applied force per unit area. A material is said to show perfectly *elastic* behavior when the stress-strain relationship is perfectly reversible. Furthermore if the strain is proportional to the applied stress then the behavior is known as linear elastic. Most engineering materials show approximately linear elastic behavior up to the onset of plastic deformation. Such behavior was originally described by Hooke and is therefore sometimes known as Hookean.

An important part of mechanical engineering design involves the computation of the distribution of strains in a structure when subject to the stresses imposed in service. Stresses may be imposed by fluid pressure or by fluid motion and also by nonuniform thermal expansion during changes in temperature. Elastic properties are traditionally regarded as being non-structure sensitive but there is one important aspect in which this is not true. The individual grains or crystals of metals are elastically anisotropic. Thus the elastic constants are a function of the orientation of the grain with respect to the orientation of the imposed stresses. The process of manufacture of components tends to introduce a certain degree of preferred orientation of the individual grains composing the structure and thus to introduce elastic anisotropy. It is probable that the existence of various degrees of preferred orientation in test specimens has led to the rather wide scatter in data for the elastic

properties of metals and alloys. Because this scatter can introduce errors of as much as 20% in some cases in computing strains, the subject is dealt with in depth in this section. Table 5.5.8(3) should be regarded only as an example of the type of information in the literature. There is no reason to suppose, for example, that steels with 5-9% chromium should differ significantly in Young's modulus from those containing slightly smaller or larger amounts of chromium as shown in that table.

Design codes require that stresses are less than the yield stress in a range in which structural materials are assumed to show linear elastic behavior. The behavior of real materials, however, is only approximately elastic so that on loading and unloading below the yield stress a narrow hysteresis loop is generated. For this reason materials have a **nonzero** damping capacity. The extent of the departure from elastic behavior becomes greater as the stress increases. Increases in the duration of loading and rise in temperature usually cause increased departure from elastic behavior. For many design purposes, perfect linear elastic behavior is assumed. The finer points of stress-strain behavior are included in this section since they could become very important. For example, the damping capacity of a heat exchanger tube might increase by an order of magnitude when the tube is pressurized. Similarly the elastic constants and damping capacity show significant changes when the temperature is increased in service, causing discrepancies between the behavior during testing cold and unpressurized and in service.

The present section therefore not only describes and defines the various ideal linear elastic moduli that are used in elementary engineering design but also indi-

cates the major sources of error that can arise when the elastic behavior of real materials is not understood. The application of elastic properties in design and analytical procedures is discussed in Part 4 and includes calculation of stress-strain distributions in complex structures, linear elastic fracture mechanics, and vibration studies.

B. Static and dynamic properties

Since the velocity of sound is not infinite in metals, the sudden application of a stress causes initially only a local response. The stress must be maintained for a time that is long compared with the time for the stress wave to travel throughout the specimen and for the vibrations to die out before the external strain becomes steady in a perfectly elastic solid. Where a problem **specifically** involves the rapid application of stress for short times or the application of rapidly alternating stresses to a perfectly elastic solid, the problem can be treated by considering the specimen to be divided into small elements of volume, each sufficiently small for the stress and the strain throughout each element of volume to be regarded as uniform.

It is commonly supposed that the elastic constants of real materials are physical properties which are not structure sensitive and therefore depend only on a linear average of the interatomic force-interatomic distance relationship (interatomic potentials). Inspection of tabulated data in standard reference books indicates that this assumption is only approximate. For example, there is a consistent difference in the elastic properties of materials in the annealed and in the cold worked conditions. A significant part of the contribution to the total strain suffered when a stress is applied arises from time-dependent, thermally activated relaxation processes involving movements of some atoms by one or more interatomic distances. For a stress applied in the nominally elastic range, most of the atoms would move with respect to their neighbors by a much smaller **distance**—typically less than 0.1% of the interatomic distance.

The relative contribution to the total strain of the atoms undergoing large movement is greater at high stresses and at elevated temperatures. The **structure-sensitive** and time-dependent nature of the elastic properties under such conditions becomes even more obvious. Values for Young's modulus of steel at 600° C may differ by a factor of 2 between quasistatic and acoustical conditions, or between creep-resistant steel and soft steel [1].

All the elastic properties of a given material vary with temperature. When a material is heated it expands and the overall interatomic distance increases, with a corresponding reduction in the interatomic forces. Thus, part of the reduction in elastic modulus is not time dependent. In addition, however, the increased availability of thermal energy at elevated temperatures increases

the number of relaxation processes that can occur, and so there is a further increased time-dependent strain contribution. Thus the dynamic properties change less rapidly with temperature than the quasistatic properties. For example, the quasistatic value of Young's modulus for steel drops by 50% between room temperature and 600°C, while the drop is only about 25% when measured by an acoustical technique [1].

C. The stress-strain curve

Two important types of load extension curve are illustrated in Figs. 1 and 2. Such curves are generated typically by applying a gradually increasing tensile load to a standard specimen (Fig. 3). For each applied load the extension (elongation) of the specimen is measured between gauge marks on the plain shank of the specimen. The load can be converted to stress by dividing by the current value of the cross section for each load as the load increases. The extension can be converted to a single value of strain only while the strain remains uniform along and across the specimen.

A specimen is said to show elastic behavior when for each stress state there is a unique set of strains. Thus for example, the length of a tensile specimen showing perfect elastic behavior is the same for a given stress whether approached from a higher or lower stress. In real materials the behavior can only approximate true elastic behavior since the damping capacity inevitably has a **nonzero** value, and therefore there must be some elastic hysteresis. Above the elastic limit the unloading curve can be distinguished experimentally from the loading curve.

In the following definitions stress is equivalent to intensity of stress and is the load (force) applied to unit

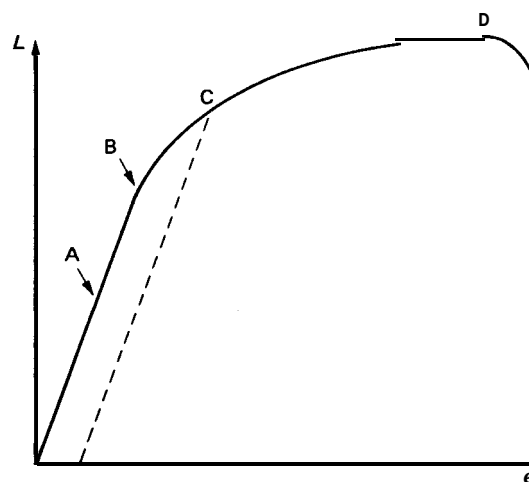


Figure 1 Applied tensile load L versus resulting extension e . A—linear elastic region; B—limit of proportionality; C—0.1% proof stress = load/cross sectional area of specimen. The broken line is drawn parallel to A to intersect the extension axis at 0.1% extension (strain). D—maximum load; F—point of fracture..

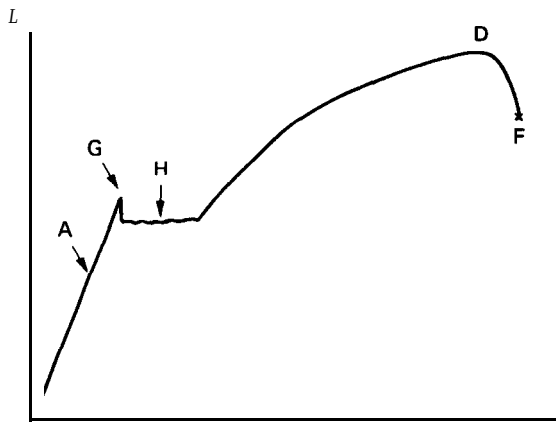


Figure 2 Load-extension curve for a material showing an upper yield point G and lower yield extension H. Other labels are as for the previous figure.

area. The dimensions of stress are the same as those of pressure and hence in SI units are measured in **pascals**. **Strain** is equivalent to intensity of strain and is the displacement per unit length caused by applying a stress. It is a dimensionless quantity.

On the load extension curves, Figs. 1 and 2, A is the linear **elastic** region. In this region strain is proportional to stress; i.e., the material obeys Hooke's law. Point B, Fig. 1—the lowest stress at which departure from a straight line can be detected—is the **limit of proportionality**. Beyond B the material may still show approximate elastic behavior. In many materials departure from linearity is gradual and therefore it is not easy to detect the point B experimentally. For such materials a point C, called the **proof** stress is defined, where the strain exceeds that for linear elastic behavior by an arbitrary amount such as 0.1% (0.1% proof stress).

Other types of material, particularly the ferritic steels, show a sudden departure from linear elastic behavior when the stress is increased to the point G, Fig. 2, called the **upper yield** stress, where there is a drop in load followed by a region of constant load, the **lower yield** stress, a regime of inhomogeneous plastic strain. The upper yield stress is increased as the duration of the applied load decreases [2]. The maximum load (point D) divided by the original cross-sectional area of the specimens is known as **the ultimate tensile strength (UTS)**.

D. Elastic properties of isotropic materials

Young's modulus E , also known as the tensile modulus, the modulus of extensibility, or the elastic modulus, is

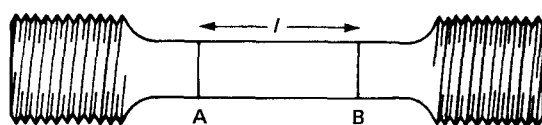


Figure 3 Standard, plain, round tensile test specimen. l is the gauge length; A and B are gauge marks.

the tensile stress divided by the strain in the direction of the applied stress, measured in the stress range in which behavior is linear elastic. It is the constant of proportionality in Hooke's law and is also the slope of the linear part of the true stress-strain curve. The dimensions are the same as those for stress (pressure).

The shear modulus G , also known as the torsion modulus or the modulus of rigidity is given by the shear stress divided by the shear strain. A shear stress applied to an isotropic specimen or a cubic metal causes change in shape without change in volume. The shear stress is taken as the magnitude of the applied force divided by the area to which the shearing force is applied. The strain is measured as the tangent of the angle θ in Fig. 4.

The **bulk** modulus K , or modulus of compressibility, is defined as the applied hydrostatic pressure increase divided by the resulting proportional decrease in volume, $-dV/V$. It differs entirely from the shear modulus in that for isotropic material and for cubic metals it is a measure of resistance to change in volume with no change in shape.

Poisson's ratio ν is a dimensionless quantity given by the change in lateral strain divided by the change in longitudinal strain when a uniaxial stress is applied along the length of a specimen. Values of ν range in principle from zero, that is, no lateral contraction when a tensile stress is applied, up to a value of $\frac{1}{2}$, that is, no change in volume when a tensile stress is applied. No metals possess the extreme values. A value of zero would imply a highly directional chemical bonding. Beryllium does approach this value in that $\nu = 0.06$. A value of $\frac{1}{2}$ would imply a material with a rigidity modulus equal to zero. The very ductile metals such as gold, silver, and lead have values of about 0.4. Liquids would have the values of $\frac{1}{2}$.

For fully isotropic materials there are only two independent parameters in this group. Given values of any two of them, it is possible to calculate the remainder using the relationships given below.

For the shear modulus,

$$G = \frac{3K(1 - 2\nu)}{2(1 + \nu)} = \frac{E}{2(1 + \nu)} = \frac{3EK}{9K - E} \quad (1)$$

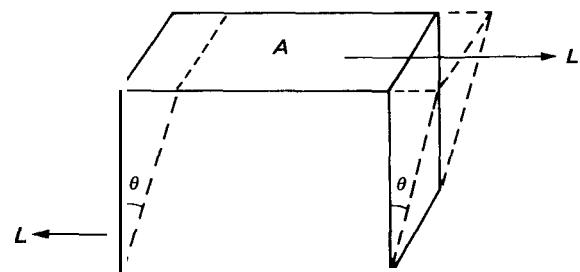


Figure 4 Broken line indicates the new position after the shearing load L is applied to the area A . The shear modulus $G = L/A \tan \theta$.

For Young's modulus,

$$E = 3K(1 - 2\nu) = 2G(1 + \nu) = \frac{9KG}{G + 3K} \quad (2)$$

For the bulk modulus,

$$K = \frac{2G(1 + \nu)}{3(1 - 2\nu)} = \frac{E}{3(1 - 2\nu)} = \frac{EG}{9G - 3E} \quad (3)$$

For Poisson's ratio,

$$\nu = \frac{E - 2G}{2G} = \frac{3K - E}{6K} = \frac{3K - 2G}{6K + 2G} \quad (4)$$

In materials not showing a marked yield point, just beyond the limit of proportionality the slope of the curve in Fig. 1 is less than the slope in the linear region. A tangent to a true stress-strain curve would indicate the response when small stresses are superimposed on a large static stress. The **local** value of the slope is known as the **tangent modulus**. It might be of some significance in heat exchanger design.

The **secant modulus** is the slope of a line joining a point on the stress-strain curve to the origin. For very soft materials some of the low static values of Young's modulus that have been published are probably more correctly described as secant moduli.

E. Elastic anisotropy

As mentioned in Sec. A, the properties of a commercial material are determined by the combined effects of the properties of the individual grains—individual single crystals—of which the material is composed. The individual grains are generally anisotropic in their elastic properties [3], i.e., the strain generated depends on the orientation of the applied stress with respect to the crystal orientation of the grain. The degree of anisotropy varies from one group of materials to another. Also fabrication processes including deformation and annealing stages introduce varying degrees of preferred orientation of the grains and hence the **final** products themselves may show varying degrees of elastic anisotropy. The nature of elastic anisotropy in metals is discussed here.

For a general single crystal of low symmetry the complete stress tensor relates stress to strain as a function of crystal directions.

A special notation is used for single crystal elastic constants. The three orthogonal crystal axes are represented by numbers:

$$x = 1 \quad y = 2 \quad z = 3$$

The shorthand notation for the coefficients relating stress to strain is

$$11 = 1 \quad 22 = 2 \quad 33 = 3$$

$$23 = 4 \quad 31 = 5 \quad 12 = 6$$

Thus $C_{11} = C_{1111}$, $C_{44} = C_{2323}$, $C_{66} = C_{1212}$, etc. Hooke's law for the xy shear is

$$\sigma_{12} = C_{1212} \epsilon_{12}$$

i.e.,

$$\sigma_{xy} = C_{66} \epsilon_{xy}$$

The general form of the stress tensor in the shorthand notation for a crystal of the lowest symmetry is

$$\sigma_i = C_{ij} \epsilon_j$$

where i takes the values 1-6 down the rows and j takes the values 1-6 across the columns.

For single crystals of most metals the symmetry is such that some of the coefficients are zero while others have common values. For example, for single crystals of a close-packed hexagonal metal such as titanium the coefficients reduce to

$$\begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{12} & C_{11} & C_{13} & 0 & 0 & 0 \\ C_{13} & C_{13} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66} \end{bmatrix}$$

i.e., $C_{44} = C_{55}$, $C_{22} = C_{11}$, etc., and where $C_{66} = \frac{1}{2}(C_{11} - C_{12})$. The Hooke's law equations are for hexagonal metals:

$$\sigma_{xx} = C_{11} \epsilon_{xx} + C_{12} \epsilon_{yy} + C_{13} \epsilon_{zz}$$

$$\sigma_{yy} = C_{12} \epsilon_{xx} + C_{11} \epsilon_{yy} + C_{13} \epsilon_{zz}$$

$$\sigma_{zz} = C_{13} \epsilon_{xx} + C_{13} \epsilon_{yy} + C_{33} \epsilon_{zz}$$

$$\sigma_{yz} = C_{44} \epsilon_{yz} \quad \sigma_{zx} = C_{44} \epsilon_{zx}$$

$$\sigma_{xy} = C_{66} \epsilon_{xy} \quad C_{66} = \frac{1}{2}(C_{11} - C_{12})$$

The elastic constants are unchanged if the axes are rotated about the **hexad**, z axis, which has sixfold symmetry. Young's modulus takes extreme (different) values for tension in the direction of the **hexad** axis and in directions at right angles to it.

Three different shear moduli are possible:

1. C_{44} , the mode for shear on the basal plane;

2. $C_{66} = \frac{1}{2}(C_{11} - C_{12})$, the mode for prismatic shear;

3. $C^* = C_{11} + C_{12} + 2C_{33} - 4C_{13}$, a complex shear corresponding to a change in axial ratio at constant volume.

Values for the c coefficients of hexagonal metal single crystals are quoted in Table 5.5.8(1).

The face-centered-cubic and body-centered-cubic metal single crystals have a higher degree of symmetry.

The c coefficients take only three different values, because the x , y , and z axes are equivalent. Thus,

$$C_{11} = C_{33} \quad C_{12} = C_{13} \quad C_{44} = C_{66}$$

Anisotropy of the shear modes are still possible; thus $\frac{1}{2}(C_{11} - C_{12}) \neq C_{44}$. The ratio $\frac{1}{2}(C_{11} - C_{12})/C_{44}$ is known as the anisotropy ratio, and for isotropic material equals unity. Some values of the c coefficients for cubic metals are shown in Table 5.5.8(2).

If materials for structural applications consist of a fine-grain structure in which individual crystals have random crystal orientations a pseudomacroscopic elastic isotropy is achieved. Working processes, such as those involved in the drawing of tube or wire, introduce some degree of preferred orientation and hence some elastic anisotropy is introduced.

Since the individual grains of a polycrystalline aggregate of most materials are elastically anisotropic, application of an external stress gives rise to an internal stress pattern. Thus the stress and strain states of the individual grains are not the same as the macroscopic average state of the specimen. In addition, most structural materials contain distributed second-phase particles having different elastic moduli from those of the matrix phase, which give rise to further internal stresses.

F. Anelasticity-damping capacity

When a metal specimen is subjected to stress cycles, energy is absorbed. Similarly, a single impact sets up vibrations that gradually die away because energy is absorbed during each cycle.

Some of the energy-absorbing processes arise from the movement of solute atoms and crystal defects. Thus damping is both a structure-sensitive and temperature-sensitive property. The processes giving rise to damping have been described in detail by Zener [4]. While many of the processes involve a monotonic increase in damping with increase in temperature and absolute stress level [4, 5], others show sharp peaks as a function of temperature at constant frequency or as a function of frequency at constant temperature [4, 6]. One of the major contributions to damping in metals involves relaxation processes at grain boundaries. For this reason a single crystal even of a very soft metal may have very low damping capacity. Contributions to damping can

arise from the flow of heat evolved when a metal undergoes elastic strain, and also from thermally activated processes including hopping of solute atoms from one lattice position to another, the bowing of dislocations, and atomic movements at the grain boundary.

Damping capacity can be expressed as dE/E , the fraction of the maximum strain energy dissipated per cycle; or λ , the logarithmic decrement; or as $\tan \delta$ where δ is the angle of lag between strain and stress; or as Q^{-1} , defined for oscillatory electrical circuits; or as $\Delta f/f$, the ratio of the width of the resonance at half amplitude to the resonant frequency. When the damping capacity is small these quantities are all simply related as follows:

$$\frac{\Delta E}{E} = 2\lambda = 2\pi \tan \delta = 2\pi Q^{-1} = \frac{2\pi \Delta f}{\sqrt{3}f}$$

For structural materials $\Delta E/E$ may range from about 10^{-3} to 5×10^{-2} but for single crystals of pure metal it may be near 10^{-5} . It is not possible to make generalized statements since the damping capacity is a function of vibration frequency, temperature, and the absolute stress level imposed. Typically, in structural materials there may be an order of magnitude increase in damping capacity of a given material between room temperature and about 600° C. At room temperature there may be an increase in damping capacity by an order of magnitude when the static stress level is raised from 0 to 240 MPa [5].

Since damping is a structure-sensitive property, the damping capacity of a material will be a distributed quantity. However, there are not sufficient data available, particularly at working temperatures and stresses, to derive the appropriate statistics.

Following the fabrication of a heat exchanger, there may be changes in the damping capacity of the structure due to processes such as shakedown when the internal stresses are redistributed and from aging processes in the metal. However, the absorption of energy in materials of construction of a heat exchanger is unlikely to make a major contribution to the total damping from all other sources.

Some of the energy-absorbing processes during vibration may give rise to cumulative changes in structure. At the tips of flaws and other stress-concentrating features the structural changes may constitute the first stages in fatigue crack growth.

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5.5

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5.5.1

Properties of saturated fluids

R. N. Maddox

■ This section contains tabular information for pure component thermophysical properties. Properties are tabulated at each of 10 temperatures as evenly spaced as is feasible between normal boiling point and critical temperature. So far as possible experimental data were used in the compilation. The user should check the reference for each property before use as this will enable him or her to ascertain whether the data were experimentally measured or calculated from a generalized correlation.

The properties tabulated are for the saturated vapor and/or liquid. At low vapor pressures these values will be essentially the same as those for the superheated gas or subcooled liquid. However, as the critical is approached there can be substantial deviation of the saturated properties from those one would normally expect to encounter. For this reason, values at saturation pressures greater than approximately 7% of the critical value should be used with extreme caution.

Figure 1 shows a typical pressure-enthalpy diagram for a single pure component. The critical point is indicated, as are the saturated vapor and liquid lines. As the temperature on the material is increased, the pressure must also increase to maintain the material in the saturated state. For this reason most of the properties for the saturated liquid and vapor are different from those frequently measured in the laboratory, or predicted by correlations. At low reduced pressures and temperatures, these differences are normally small and can be neglected. As the temperature and pressure approach the critical, however, the differences become larger and must be taken into account.

As an example of the behavior of properties for the

saturated phase, consider the enthalpies. The liquid enthalpy behaves normally until a point approximately at *A* is reached. In the region of the critical, the enthalpy increases more rapidly with temperature than at lower temperature and pressure. At the critical, presumably the liquid enthalpy increases with no change in temperature. If this seems strange, consider the vapor enthalpy. At approximately point *B*, the vapor enthalpy no longer increases with temperature, but actually begins to decrease as the temperature is increased.

The behavior of the enthalpy is reflected in the specific heat capacity. For the saturated liquid, the heat capacity in the region of the critical becomes very large, reflecting the **enthalpy** increase with little or no change

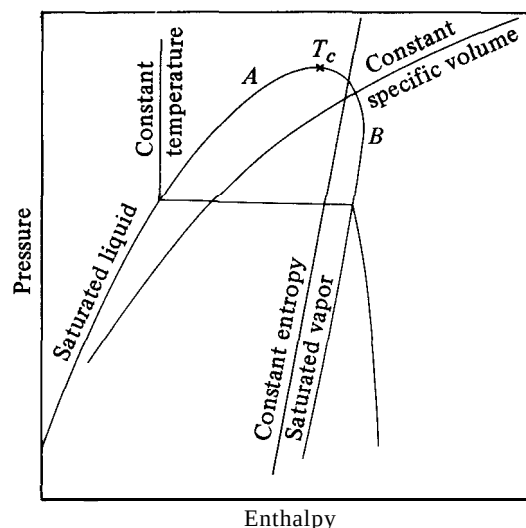


Figure 1 Typical **pressure-enthalpy** diagram for pure component.

in temperature. The saturated vapor enthalpy actually becomes negative to accommodate the decrease in enthalpy as the material approaches its critical temperature.

Values from the tables may be interpolated. However, there should be no extrapolation to higher temperatures and/or pressures.

Guidelines for interpolation of data are as follows:

Saturation (vapor) pressure values at intermediate temperatures can be interpolated by use of the linearity of log vapor pressure with reciprocal absolute temperature. For most of the compounds, particularly at temperatures removed from the critical temperature, this line should be straight.

Liquid density. Over restricted ranges of temperature liquid density, except in the region of the critical, should be plotted as a straight line function of temperature. In the region of the critical there will be some curvature.

Vapor density values should plot as a reasonably straight line with temperature.

Liquid enthalpy should plot as a smooth curve function of temperature.

Vapor enthalpy values should plot as a smooth curve function of temperature.

Heat of vaporization values can be satisfactorily interpolated by plotting heat of vaporization as a function of temperature.

Liquid heat capacities plot satisfactorily as smooth curves as a function of temperature.

Vapor heat capacities plot satisfactorily as smooth curves as a function of temperature.

Liquid viscosity can be interpolated by plotting log

viscosity as a function of reciprocal absolute temperature. Contrary to most conceptions this will not, in general, be a straight line. However, curvature will be slight and will allow satisfactory interpolation of values.

Vapor viscosity values plot satisfactorily as smooth curves as a function of temperature.

Liquid thermal conductivity values can be plotted satisfactorily as a function of temperature. The line will **not** be straight. However curvature is slight and should allow for satisfactory interpolation.

Vapor thermal conductivity values can be interpolated by plotting as a function of temperature.

Liquid Prandtl number. Values for liquid Prandtl number can be interpolated by plotting as a function of temperature.

Vapor Prandtl numbers can be interpolated by plotting as a function of temperature.

Interfacial tension values can be interpolated by plotting as a function of temperature.

Coefficient of thermal expansion values can be interpolated by plotting as a function of temperature. Coefficient of thermal expansion is based on the density at the normal boiling point.

Naturally, mathematical interpolation is possible for any of the values. The only thing that must be done is to use the appropriate equation for interpolation of values. This may be a source of trouble in some cases (liquid viscosity, for example) where the equation used does not truly linearize the property value. Analysis of the error between calculated and tabulated values will show if the errors are too large.

Preceding the saturation tables is a table of conversion factors.

Conversion factors for saturation property tables

Quantity	Symbol	unit	Abbreviation	Equivalent in pure S.I.	Equivalent in British units	Other equivalents
Saturation temperature	T_{sat}	kelvin	K	K	1.8°R	—
Saturation pressure	p_{sat}	kilopascals	kPa	10^3 N/m^2	0.145 1 lbf/in ²	0.01 bar
Liquid phase density	ρ_l	kilograms per cubic meter	kg/m ³	kg/m ³	0.062 43 lb/ft ³	0.001 g/cm ³
Vapor phase density	ρ_g	kilograms per cubic meter	kg/m ³	kg/m ³	0.062 43 lb/ft ³	0.001 g/cm ³
Liquid phase enthalpy	h_l	kilojoules per kilogram	kJ/kg	10^3 J/kg	0.429 9 Btu/lb	0.238 8 cal/g
Vapor phase enthalpy	h_g	kilojoules per kilogram	kJ/kg	10^3 J/kg	0.429 9 Btu/lb	0.238 8 cal/g
Heat of vaporization	$\Delta h_{g,l}$	kilojoules per kilogram	kJ/kg	10^3 J/kg	0.429 9 Btu/lb	0.238 8 cal/g
Liquid specific heat capacity	$c_{p,l}$	kilojoules per kilogram per kelvin	kJ/(kg K)	10^3 J/(kg K)	0.238 8 Btu/(lb °F)	0.238 8 cal/(g °C)
Vapor specific heat capacity	$c_{p,g}$	kilojoules per kilogram per kelvin	kJ/(kg K)	10^3 J/(kg K)	0.238 8 Btu/(lb °F)	0.238 8 cal/(g °C)
Liquid dynamic (absolute) viscosity	η_l	micronewtons second per square meter	$\mu\text{Ns/m}^2$	10^{-6} Ns/m^2	0.002 419 lb/(ft h)	0.001 centipoise
Vapor dynamic (absolute) viscosity	η_g	micronewtons second per square meter	$\mu\text{Ns/m}^2$	10^{-6} Ns/m^2	0.002 419 lb/(ft h)	0.001 centipoise
Liquid thermal conductivity	λ_l	milliwatts per square meter per kelvin-per-meter	(mW/m ²)/(K/m)	(10^{-6} W/m^2)/(K/m)	0.000 577 8 (Btu/h ft ²)/(°F/ft)	—
Vapor thermal conductivity	λ_g	milliwatts per square meter per kelvin-per-meter	(mW/m ²)/(K/m)	(10^{-6} W/m^2)/(K/m)	0.000 577 8 (Btu/h ft ²)/(°F/ft)	—
Liquid Prandtl number	Pr_l	dimensionless	—	—	—	—
Vapor Prandtl number	Pr_g	dimensionless	—	—	—	—
Surface tension	σ	millinewtons per meter	mN/m	10^{-3} N/m	—	1 dyne/cm
Coefficient of thermal expansion for liquid phase	$\beta_{e,l}$	1/kilokelvin	kK ⁻¹	10^{-3} K^{-1}	0.000 555 6°R ⁻¹	—

^aTo obtain the quantity in the desired units, multiply the quantity in the table by the factor preceding the units. For example, a density of 1 000 kg/m³ corresponds to a density in British units of 1 000 X 0.062 43 = 62.43 lb/ft³.

Tabular information on saturated properties is given for the following compounds:

HYDROCARBONS

Paraffins

Methane

Ethane

Propane

Dimethyl propane (neopentane)

i-Butane

n-Butane

iPentane

n-Pentane

n-Hexane

n-Heptane

n-Octane

n-Nonane

n-Decane**Cyclics**

Cyclopentane

Cyclohexane

Aromatics

Benzene

Toluene

m-Xylene

o-Xylene

p-Xylene

Ethyl benzene

Unsaturates

Acetylene

Ethylene

Propylene

1,3-Butadiene**1,2-Butadiene**

ALCOHOLS

Methanol

Ethanol

1-Propanol**2-Propanol**

n-Butanol

t-Butyl alcohol

Phenol

REFRIGERANTS

Refrigerant 12

Refrigerant 13

Refrigerant 21

Refrigerant 22

MISCELLANEOUS

Ethyl ether

Methyl-t-butyl ether

Ethylene oxide

Propylene oxide

Methyl acetate

Ethyl acetate

Chloroform

Aniline

Acetic acid

Acetone

Dowtherm A**Dowtherm J**

INORGANICS AND ELEMENTS

Air

Ammonia

Argon

Carbon dioxide

Carbon monoxide

Carbon tetrachloride

Chlorine

Fluorine

Helium

Hydrogen

Hydrogen chloride

Hydrogen fluoride

Hydrogen sulfide

Mercury

Neon

Nitrogen

Oxygen

Water

METHANE=

Chemical formula: CH₄
Molecular weight: 16.042
Normal boiling point: 111.42 K
Melting point: 90.66 K

Critical temperature: 190.55 K
Critical pressure: 4 64 1 kPa
Critical density: 162 kg/m³

T_{sat} , K	111.42	120	130	140	150	160	170	180	185	190	
p_{sat} , kPa	101	192	367	638	1033	1 588	2 338	3 288	3854	4552	[1]
ρ_L , kg/m ³	424.3	412.0	396.7	379.8	361.0	339.3	312.3	271.9	240.0	182.0	[1]
ρ_g , kg/m ³	1.79	3.26	5.95	10.03	16.08	25.03	38.57	59.14	76.28	120.9	[1]
h_L , kJ/kg	716.3	747.0	784.1	821.9	860.0	901.4	948.4	1011.1	1057.0	1133.4	[1]
h_g , kJ/kg	1228.1	1241.8	1255.7	1 267.2	1 274.9	1 277.6	1 273.3	1 258.9	1 245.0	1 203.2	[1]
$\Delta h_{g,L}$, kJ/kg	511.8	494.8	471.8	445.3	414.9	376.2	324.9	247.8	188	69.8	[1]
$c_{p,L}$, kJ/(kg K)	3.43	3.53	3.63	3.77	3.94	4.12	5.16	7.45	11.3	70.5	[3, 9]
$c_{p,g}$, kJ/(kg K)	2.07	2.11	2.19	2.33	2.53	2.90	3.62	5.95	6.33	277.5	[1, 11]
η_L , $\mu\text{Ns/m}^2$	106.5	86.05	71.65	61.26	52.24	44.54	37.69	30.98	26.92	19.34	[1]
η_g , $\mu\text{Ns/m}^2$	4.49	4.84	5.28	5.74	6.27	6.89	7.69	8.89	9.84	12.96	[1]
λ_L , (mW/m ²)/(K/m)	193	178	163	148	133	118	103	88	80	73	[2]
λ_g , (mW/m ²)/(K/m)	12.1	12.9	16.4	19.6	23.0	27.6	33.1	39.9	45.3	62.0	[9]
Pr_L	1.88	1.70	1.60	1.56	11.55	1.56	1.89	2.62	3.80	18.8	[12]
Pr_g	0.77	0.79	0.71	0.68	0.69	0.72	0.83	1.33	1.38	58.01	[12]
σ , mN/m	13.5	11.5	9.28	7.22	5.31	3.58	2.06	0.81	0.33	0.01	[6]
$\beta_{e,L}$, K^{-1}	2.27	3.46	4.37	5.18	6.58	8.87	14.2	32.8	58.6	385	[10]

See page 5.5.1-3 for definition of symbols and page 5.5.1-2 for discussion of interpolation methods.

ETHANE

Chemical formula: CH_3CH_3

Molecular weight: 30.068

Normal boiling point: 184.52 K

Melting point: 89.88 K

Critical temperature: 305.5 K

Critical pressure: 4 913 kPa

Critical density: 212 kg/m³

T_{sat} , K	184.52	200	210	230	240	260	270	280	290	300	
p_{sat} , kPa	101	217	334	700	968	1712	2 208	2 801	3510	4 365	[1]
ρ_l , kg/m ³	546.45	529.10	516.79	489.7 1	474.60	440.14	419.81	396.35	364.56	316.25	[1]
ρ_g , kg/m ³	2.04	4.09	6.21	12.75	17.56	31.65	42.03	55.96	77.10	119.18	[1]
h_l , kJ/kg	399.52	437.50	462.53	415.34	541.41	598.79	629.79	663.10	700.28	753.08	[1]
h_g , kJ/kg	889.19	903.74	912.82	929.18	935.72	943.27	943.23	941.14	930.10	892.31	[1]
$\Delta h_{g,l}$, kJ/kg	489.67	466.24	450.29	414.84	394.31	344.48	313.44	278.04	229.82	139.23	[1]
$c_{p,l}$, kJ/(kg K)	2.42	2.48	2.54	2.66	2.70	3.00	3.18	3.42	3.80		[3, 5]
$c_{p,g}$, kJ/(kg K)	1.40	1.48	1.54	1.70	1.79	2.13	2.42	2.94	3.31	9.5 1	[11]
η_l , $\mu\text{Ns/m}^2$	168	139	124	99.4	88.8	70.8	61.6	54.0	46.0	36.1	[4]
η_g , $\mu\text{Ns/m}^2$	6.00	6.59	7.03	7.89	8.42	9.85	10.9	12.1	14.2	19.0	[4, 15]
λ_l , (mW/m ²)/(K/m)	157	146	140	126	117	99.2	92.1	83.9	76.0	67.4	[7]
λ_g , (mW/m ²)/(K/m)	8.6	10.3	11.5	14.1	15.5	18.6	20.7	22.8	26.1	32.0	[2, 14]
Pr_l	2.59	2.37	2.26	2.10	2.05	2.14	2.12	2.2	2.23		[12]
Pr_g	0.98	0.95	0.94	0.95	0.97	1.13	1.27	1.56	1.80	5.64	[12]
σ , mN/m	15.86	13.28	11.71	8.51	6.85	4.28	3.14	2.00	1.14	0.43	[6]
$\beta_{e,l}$, K^{-1}	2.01	2.31	2.58	3.32	3.80	5.46	6.67	9.40	15.9	96.2	[10]

PROPANE

Chemical formula: $\text{CH}_3\text{CH}_2\text{CH}_3$

Molecular weight: 44.094

Normal boiling point: 231.10 K

Melting point: 85.47 K

Critical temperature: 370.00 K

Critical pressure: 4 264 kPa

Critical density: 225 kg/m³

T_{sat} , K	231.1	248.06	259.83	275.24	291.83	317.42	330.70	351.23	359.61	367.18	
p_{sat} , kPa	101	203	304	507	810	1520	2 026	3 039	3 545	4 052	[1]
ρ_l , kg/m ³	582	562	549	528	504	460	434	381	347	300	[1]
ρ_g , kg/m ³	2.42	4.63	6.77	11.0	17.5	33.9	47.1	80.4	104	150	[1]
h_l , kJ/kg	421.2	459.7	485.2	522.5	563.1	631.8	672.8	745.7	781.7	829.0	[1]
h_g , kJ/kg	847.4	866.7	879.2	895.6	911.0	929.5	937.4	942.4	934.9	915.6	[1]
$\Delta h_{g,l}$, kJ/kg	426.2	407.0	394.0	373.1	347.9	297.7	264.6	196.7	153.2	86.6	[1]
$c_{p,l}$, kJ/(kg K)	2.24	2.32	2.38	2.47	2.58	2.78	3.27	4.27	6.62		[1, 31]
$c_{p,g}$, kJ/(kg K)	1.37	1.51	1.65	1.88	2.27	3.37	4.14	6.16	7.01	11.42	[1, 9, 111]
η_l , $\mu\text{Ns/m}^2$	208.7	177.4	154.9	134.5	114.7	85.7	72.4	51.2	41.0	25.4	[4]
η_g , $\mu\text{Ns/m}^2$	6.0	7.0	7.3	7.5	8.5	9.6	10.3	12.1	14.9	20.1	[4]
λ_l , (mW/m ²)/(K/m)	134	124	117	108	99	84	76	64	59		[6]
λ_g , (mW/m ²)/(K/m)	10.7	12.8	14.1	15.9	17.8	21.7	23.9	28.1	31.0	36.1	12, 141
Pr_l	3.49	3.26	3.15	3.08	2.99	2.84	3.07	3.41	4.60		[12]
Pr_g	0.77	0.83	0.85	0.89	1.08	1.49	1.78	2.65	3.37	6.36	[12]
σ , mN/m	15.5	14.25	13.2	9.5	7.5	4.6	3.0	1.4	1.0	0.4	[6]
$\beta_{e,l}$, K^{-1}	2.01	2.21	2.45	2.90	3.60	5.19	6.52	15.2	23.1		[10]

DIMETHYL PROPANE (NEOPENTANE)Chemical formula: $C(CH_3)_4$

Molecular weight: 72.15

Normal boiling point: 282.65 K

Melting point: 256.58 K

Critical temperature: 433.78 K

Critical pressure: 196 kPa

Critical density: 238 kg/m³

T_{sat}, K	282.65	305	320	335	350	365	380	395	410	433.78	
P_{sat}, kPa	101.3	215	362	482	676	945	1 280	1 700	2 200	3 196	
$\rho_L, kg/m^3$	603	575	558	543	519	497	472	443	407	238	[51]
$\rho_g, kg/m^3$	3.28	6.38	9.91	14.5	20.7	29.0	40.2	55.8	79.1	238	[51, 62]
$h_L, kJ/kg$	-111	-50	-25	13	51	91	128	175	221	329	[67]
$h_g, kJ/kg$	204	237	260	282	305	327	347	366	379	329	[63, 62, 69]
$\Delta h_{g,L}, kJ/kg$	315	297	284	269	254	236	219	191	158		[51]
$c_{p,L}, kJ/(kg K)$	2.14	2.27	2.37	2.48	2.63	2.77	2.96	3.20	3.59		[70]
$c_{p,g}, kJ/(kg K)$	1.65	1.80	1.91	2.03	2.16	2.32	2.53	2.85	3.51		[63, 62]
$\eta_L, \mu Ns/m^2$	280	211	169	140	112	94	82	69	61	36	[71, 33]
$\eta_g, \mu Ns/m^2$	6.89	7.44	7.88	8.27	8.73	9.25	9.87	10.3	11.8	36	[9, 51, 14]
$\lambda_L, (mW/m^2)/(K/m)$	90	84	80	76	72	67	63	58	54	42	[34, 51, 22]
$\lambda_g, (mW/m^2)/(K/m)$	13.2	15.0	16.3	18.0	19.8	21.6	24.2	26.6	30.8	42	[51, 22]
Pr_L	6.66	5.70	5.01	4.57	4.09	3.89	3.85	3.81	4.06		[12]
Pr_g	0.86	0.89	0.92	0.93	0.95	0.99	1.03	1.10	1.34		[12]
$\sigma, mN/m$	12.9	10.6	9.11	7.67	6.21	4.93	3.65	2.45	1.34		[23]
$\beta_{e,L}, K^{-1}$	1.80	2.11	2.38	2.72	3.18	3.83	4.81	6.41	9.99		[10]

ISOBUTANEChemical formula: $(CH_3)_2CHCH_3$

Molecular weight: 58.12

Normal boiling point: 261.4 K

Melting point: 113.55 K

Critical temperature: 408.1 K

Critical pressure: 3 647 kPa

Critical density: 221 kg/m³

T_{sat}, K	261.4	285	300	315	330	345	360	375	390	408.1	
P_{sat}, kPa	101.3	233	355	553	805	1 132	1 540	2 066	2 697	3 647	[1]
$\rho_L, kg/m^3$	594	567	550	529	508	485	455	422	377	221	[1]
$\rho_g, kg/m^3$	2.87	6.33	9.81	14.6	21.2	30.0	42.2	59.7	87.3	221	[1]
$h_L, kJ/kg$	232.5	286.1	323.3	360.5	397.7	437.3	481.5	528.0	574.5	697.8	[15]
$h_g, kJ/kg$	591.8	623.4	646.6	667.6	686.2	704.8	721.1	737.3	744.3	697.8	[15]
$\Delta h_{g,L}, kJ/kg$	365.2	337.3	323.3	307.1	288.5	267.5	239.6	209.3	169.8		[15]
$c_{p,L}, kJ/(kg K)$	2.12	2.34	2.45	2.56	2.68	2.79	2.95	3.16	3.59		[55, 58]
$c_{p,g}, kJ/(kg K)$	1.53	1.69	1.81	1.94	2.09	2.28	2.55	3.00	4.18		[63, 62]
$\eta_L, \mu Ns/m^2$	240	190	145	116	101	86	74	61	44	34	171,331
$\eta_g, \mu Ns/m^2$	6.7	7.4	8.0	8.6	9.1	9.7	10.4	11.3	12.9	34	[1, 141]
$\lambda_L, (mW/m^2)/(K/m)$	100	92	87	83	80	77	73	68	61	42.4	[34]
$\lambda_g, (mW/m^2)/(K/m)$	11.6	14.4	16.3	18.3	20.4	22.7	25.2	27.9	31.2	42.4	164,221
Pr_L	5.09	4.83	4.08	3.58	3.38	3.12	2.99	2.83	2.59		[12]
Pr_g	0.88	0.88	0.89	0.91	0.93	0.97	1.05	1.22	1.73		[12]
$\sigma, mN/m$	14.1	11.4	9.7	8.1	6.5	5.0	3.6	2.3	1.1		[65]
$\beta_{e,L}, K^{-1}$	1.87	2.22	2.52	2.91	3.44	4.20	5.40	7.56	12.8		[10]

n-BUTANE

Chemical formula: CH₃, CH₂, CH₃, CH₃
 Molecular weight: 58.12
 Normal boiling point: 272.66 K
 Melting point: 134.82 K

Critical temperature: 425.16 K
 Critical pressure: 3 796 kPa
 Critical density: 225.3 kg/m³

T_{sat} , K	273.15	289	305	321	337	353	369	385	405	425.16	
p_{sat} , kPa	103	184	304	469	706	1 023	1526	1925	2739	3797	1561
ρ_{L} , kg/m ³	603	587	571	551	529	504	475	441	388	225.3	[46]
ρ_{g} , kg/m ³	2.81	4.81	7.53	11.6	17.4	25.1	35.6	51.3	80.7	225.3	[56]
h_{L} , kJ/kg	-1 194	-1 158	-1 121	-1 081	-1 040	-997	-945	-896	-821	-665	[56]
h_{g} , kJ/kg	-809	-789	-769	-747	-725	-706	-681	-663	-648	-665	[56]
$\Delta h_{\text{g,L}}$, kJ/kg	385	369	352	334	315	291	264	233	173		[46]
$c_{p,\text{L}}$, kJ/(kg K)	2.34	2.47	2.59	2.68	2.80	2.95	3.11	3.36	3.80		[46]
$c_{p,\text{g}}$, kJ/(kg K)	1.67	1.76	1.88	2.00	2.15	2.33	2.62	3.03	4.76		[56]
η_{L} , $\mu\text{Ns/m}^2$	206	179	154	131	112	95	80	65	51		[4]
η_{g} , $\mu\text{Ns/m}^2$	7.35	7.81	8.32	8.87	9.44	10.20	11.25	12.17	16.30		[4]
λ_{L} , (mW/m ²)/(K/m)	114.6	109.8	104.9	100.1	95.1	90.4	85.5	80.7	14.6	48.1	[2]
λ_{g} , (mW/m ²)/(K/m)	13.69	15.19	16.82	18.57	20.47	22.49	24.69	27.24	31.2	48.7	[2]
Pr_{L}	4.20	4.02	3.80	3.51	3.30	3.11	2.89	2.72	2.59		[12]
Pr_{g}	0.90	0.90	0.93	0.96	1.00	1.06	1.19	1.42	2.48		[12]
σ , mN/m	14.8	12.8	11.0	9.10	7.29	5.54	4.03	2.75	1.34		[46]
$\beta_{e,\text{L}}$, K^{-1}	1.73	2.01	2.37	2.80	3.45	4.31	7.31	9.87	10.0		[10]

ISOPENTANE

Chemical formula: (CH₃)₂C(CH₃)₂
 Molecular weight: 72.146
 Normal boiling point: 301.0 K
 Melting point: 113.25 K

Critical temperature: 460.4 K
 Critical pressure: 3 380 kPa
 Critical density: 236 kg/m³

T_{sat} , K	301.0	325	340	355	370	385	400	415	430	460.4	
p_{sat} , kPa	101.3	217	328	476	667	913	1 222	1603	2070	3 380	[1]
ρ_{L} , kg/m ³	613	586	569	552	532	511	488	461	428	236	[1]
ρ_{g} , kg/m ³	3.07	6.30	9.41	13.5	18.9	26.2	36.0	49.3	68.3	236	[1]
h_{L} , kJ/kg	290.8	348.9	383.8	423.3	465.2	504.7	546.6	588.5	639.1	790.8	[15]
h_{g} , kJ/kg	632.1	669.9	693.1	716.4	739.7	765.3	783.9	807.1	825.1	790.8	[15]
$\Delta h_{\text{g,L}}$, kJ/kg	341.9	321.0	309.3	293.1	274.5	260.6	237.3	218.6	186.0		[15]
$c_{p,\text{L}}$, kJ/(kg K)	2.29	2.43	2.53	2.62	2.71	2.80	2.91	3.05	3.24		[55, 58]
$c_{p,\text{g}}$, kJ/(kg K)	1.72	1.86	1.96	2.08	2.20	2.34	2.54	2.81	3.28		[1, 62]
η_{L} , $\mu\text{Ns/m}^2$	201	163	146	126	111	97	84	71	60		[71, 33]
η_{g} , $\mu\text{Ns/m}^2$	7.4	8.0	8.5	9.0	9.5	9.9	10.5	11.2	12.2		[15, 14]
λ_{L} , (mW/m ²)/(K/m)	103	95	91	87	84	80	75	70	63	48.3	[34, 22]
λ_{g} , (mW/m ²)/(K/m)	14.7	17.4	19.3	21.5	23.4	25.0	27.6	29.4	33.4	48.3	[15, 46, 22]
Pr_{L}	4.47	4.17	4.06	3.79	3.58	3.40	3.22	3.05	2.99		[12]
Pr_{g}	0.87	0.86	0.86	0.87	0.89	0.93	0.97	1.07	1.20		[12]
σ , mN/m	14.0	11.5	9.9	8.4	7.0	5.6	4.3	3.0	1.9		[65]
$\beta_{e,\text{L}}$, K^{-1}	1.73	2.03	2.27	2.58	2.99	3.54	4.36	5.66	8.10		[10]

***n*-PENTANE**Chemical formula: $\text{CH}_3(\text{CH}_2)_3\text{CH}_3$

Molecular weight: 72.151

Normal boiling point: 309.2 K

Melting point: 143.4 K

Critical temperature: 469.6 K

Critical pressure: 3 369 kPa

Critical density: 273.3 kg/m

T_{sat}, K	309.2	335	350	365	380	395	410	425	440	469.6	
$p_{\text{sat}}, \text{kPa}$	101.3	227	341	492	688	935	1 249	1634	2 103	3 370	[1]
$\rho_{\text{L}}, \text{kg/m}^3$	610.2	582.9	566.0	548.0	528.9	507.9	484.1	456.5	423.5	280.9	[1]
$\rho_{\text{G}}, \text{kg/m}^3$	3.00	6.36	9.41	13.51	18.99	26.11	36.21	49.73	68.96	184.1	[1]
$h_{\text{L}}, \text{kJ/kg}$	319.8	383.8	423.3	458.2	504.7	546.6	588.5	637.3	686.2	846.7	[15]
$h_{\text{G}}, \text{kJ/kg}$	678.0	721.1	744.3	767.6	790.8	814.1	837.4	855.9	876.9	846.7	[15]
$\Delta h_{\text{fg}}, \text{kJ/kg}$	358.2	337.3	321.0	309.4	286.1	261.5	248.9	218.6	190.7		[15]
$c_{p,\text{L}}, \text{kJ/(kg K)}$	2.34	2.52	2.62	2.12	2.82	2.94	3.06	3.20	3.44		[55, 58]
$c_{p,\text{G}}, \text{kJ/(kg K)}$	1.79	1.96	2.05	2.16	2.28	2.48	2.66	2.96	3.37		[46, 20]
$\eta_{\text{L}}, \mu\text{Ns/m}^2$	196	159	140	123	108	95	83	72	60		[1]
$\eta_{\text{G}}, \mu\text{Ns/m}^2$	6.9	7.6	8.1	8.5	9.0	9.5	10.2	11.1	12.4		[1]
$\lambda_{\text{L}}, (\text{mW/m}^2)/(\text{K/m})$	107	98	93	88	83	79	75	71	69	47	[46]
$\lambda_{\text{G}}, (\text{mW/m}^2)/(\text{K/m})$	16.7	19.3	21.0	22.8	24.8	26.7	29.0	31.7	34.9	47	[46]
Pr_{L}	4.29	4.09	3.94	3.80	3.67	3.53	3.36	3.16	2.84		[12]
Pr_{G}	0.74	0.77	0.79	0.81	0.83	0.88	0.94	1.03	1.19		[12]
$\sigma, \text{mN/m}$	14.3	11.3	9.7	8.1	6.7	5.2	3.8	2.8	1.6		[51]
$\beta_{\text{e,L}}, \text{K}^{-1}$	1.40	1.93	2.21	2.52	2.92	3.54	4.48	5.95	15.5		[10]

***n*-HEXANE**Chemical formula: $\text{CH}_3(\text{CH}_2)_4\text{CH}_3$

Molecular weight: 86.178

Normal boiling point: 341.88 K

Melting point: 177.83 K

Critical temperature: 507.44 K

Critical pressure: 3 031 kPa

Critical density: 232.8 kg/m

T_{sat}, K	341.88	370	385	400	415	430	445	460	475	507.44	
$p_{\text{sat}}, \text{kPa}$	101.3	228	331	465	638	854	1 124	1457	1859	3 031	[1]
$\rho_{\text{L}}, \text{kg/m}^3$	613	585	568	551	532	511	488	463	432	233	[1]
$\rho_{\text{G}}, \text{kg/m}^3$	3.3	7.0	10.0	14.1	19.5	26.7	34.7	48.6	66.2	233	[1]
$h_{\text{L}}, \text{kJ/kg}$	395.4	465.2	507.1	546.6	586.2	632.7	676.9	725.7	774.6	930.4	[15]
$h_{\text{G}}, \text{kJ/kg}$	728.0	776.9	802.5	830.4	856.0	879.2	907.1	930.4	953.7	930.4	[15]
$\Delta h_{\text{fg}}, \text{kJ/kg}$	332.6	311.7	295.4	283.8	269.8	246.5	230.2	204.7	179.1		[15]
$c_{p,\text{L}}, \text{kJ/(kg K)}$	2.39	2.58	2.68	2.78	2.89	3.00	3.12	3.26	3.46		[55, 58]
$c_{p,\text{G}}, \text{kJ/(kg K)}$	1.91	2.07	2.18	2.28	2.39	2.51	2.66	2.92	3.32		[46]
$\eta_{\text{L}}, \mu\text{Ns/m}^2$	202.2	158.9	145.7	128.5	113.6	99.9	87.4	75.6	64.3		[1]
$\eta_{\text{G}}, \mu\text{Ns/m}^2$	7.3	7.9	8.4	8.8	9.4	10.1	10.9	11.9	13.3		[1]
$\lambda_{\text{L}}, (\text{mW/m}^2)/(\text{K/m})$	100.4	91.0	87	82	78	74.5	67.8	63.0	56.0	49.8	[15, 46]
$\lambda_{\text{G}}, (\text{mW/m}^2)/(\text{K/m})$	16.7	18.8	20.4	22.4	24.2	26.2	28.5	30.4	33.8	49.8	[46]
Pr_{L}	4.81	4.51	4.49	4.36	4.19	4.01	3.99	3.83	3.97		[12]
Pr_{G}	0.83	0.87	0.91	0.91	0.92	0.97	1.02	1.14	1.31		[12]
$\sigma, \text{mN/m}$	13.33	10.57	9.13	7.71	6.35	5.02	3.78	2.66	1.63		[1]
$\beta_{\text{e,L}}, \text{K}^{-1}$	1.28	1.86	2.17	2.46	2.88	3.41	4.14	5.41	20.0		[10]

n-HEPTANEChemical formula: $\text{CH}_3(\text{CH}_2)_5\text{CH}_3$

Molecular weight: 100.198

Normal boiling point: 371.6 K

Melting point: 182.6 K

Critical temperature: 540.6 K

Critical pressure: 2 736 kPa

Critical density: 234.1 kg/m³

T_{sat} , K	371.6	380	400	420	440	460	480	500	520	540.6	
p_{sat} , kPa	101.3	130	219	349	529	721	1094	1513	2046	2736	[1]
ρ_L , kg/m ³	614	606	585	563	540	512	484	448	397	234	[1]
ρ_g , kg/m ³	3.46	4.36	1.23	11.5	17.4	25.6	37.8	56.5	88.3	234	[1]
h_L , kJ/kg	453.6	474.5	530.3	586.2	639.7	702.5	760.6	825.7	895.5	1 004.8	[15]
h_g , kJ/kg	765.3	786.2	823.4	860.6	897.8	937.4	972.3	1009.5	1 035.1	1 004.8	[15]
$\Delta h_{g,L}$, kJ/kg	319.7	311.7	293.1	274.4	258.1	234.9	211.7	183.8	139.6		[15]
$c_{p,L}$, kJ/(kg K)	2.57	2.61	2.72	2.82	2.93	3.03	3.19	3.39	3.85		1551
$c_{p,g}$, kJ/(kg K)	1.98	2.01	2.15	2.26	2.41	2.51	2.12	3.05	3.60		[46]
η_L , $\mu\text{Ns/m}^2$	201	186	159	135	115	97	82	67	54	41	[1]
η_g , $\mu\text{Ns/m}^2$	7.3	7.1	8.3	9.0	9.7	10.7	12.1	14.0	17.6	41	[1]
λ_L , (mW/m ²)/(K/m)	98.0	95.5	88.8	82.9	76.1	69.9	61.1	52.0	41.8		[46, 61]
λ_g , (mW/m ²)/(K/m)	18.0	18.4	20.1	22.6	24.9	27.7	29.9	33.0	36.0		[46]
Pr_L	5.27	5.08	4.87	4.59	4.43	4.21	4.28	4.31	4.97		[12]
Pr_g	0.80	0.84	0.89	0.90	0.94	0.97	1.10	1.29	1.76		[12]
σ , mN/m	12.6	11.8	10.0	8.3	6.6	5.1	3.6	2.2	0.8		[1]
$\beta_{e,L}$, kK^{-1}	1.6	1.7	1.90	2.2	2.1	3.2	4.2	6.8	24.5		[10]

n-OCTANEChemical formula: $\text{CH}_3(\text{CH}_2)_6\text{CH}_3$

Molecular weight: 114.224

Normal boiling point: 398.8 K

Melting point: 216.35 K

Critical temperature: 568.8 K

Critical pressure: 2 486 kPa

Critical density: 232 kg/m³

T_{sat} , K	398.8	415	435	455	475	495	515	535	555	568.8	
p_{sat} , kPa	101.3	156	252	386	569	809	1 127	1535	2052	2486	[1]
ρ_L , kg/m ³	611	595	575	553	529	502	470	432	373	232	[1]
ρ_g , kg/m ³	3.80	5.67	8.98	13.7	20.4	29.9	44.0	65.0	105	232	[1]
h_L , kJ/kg	514.1	558.2	609.4	667.6	725.7	786.2	851.3	921.1	990.9	1088.6	[15]
h_g , kJ/kg	814.1	844.3	883.9	923.4	965.3	1 004.8	1 046.7	1081.6	1 109.5	1088.6	[15]
$\Delta h_{g,L}$, kJ/kg	300.0	286.1	274.5	255.8	239.6	218.6	195.4	160.5	118.6		[15]
$c_{p,L}$, kJ/(kg K)	2.50	2.61	2.74	2.89	3.03	3.18	3.36	3.60	4.23		[55, 58]
$c_{p,g}$, kJ/(kg K)	2.11	2.19	2.30	2.42	2.56	2.73	2.96	3.30	4.80		[46, 62]
η_L , $\mu\text{Ns/m}^2$	203	174	149	126	107	91	75	61	48		[1]
η_g , $\mu\text{Ns/m}^2$	1.4	7.9	8.5	9.2	10.0	11.1	12.5	14.7	19.4		[1, 14]
λ_L , (mW/m ²)/(K/m)	98	93	88	83	78	73	68	62	56	47.7	[15, 46]
λ_g , (mW/m ²)/(K/m)	18.4	20.3	22.5	24.3	26.7	29.1	31.6	34.4	38.6	47.7	[15, 46, 22]
Pr_L	5.18	4.88	4.64	4.39	4.16	3.96	3.71	3.54	3.63		[12]
Pr_g	0.85	0.85	0.87	0.92	0.96	1.04	1.21	1.41	2.41		[12]
σ , mN/m	11.9	10.5	8.9	7.3	5.8	4.4	2.9	1.8	0.55		[1]
$\beta_{e,L}$, kK^{-1}	1.62	1.79	2.05	2.39	2.88	3.60	4.82	6.96	15.9		[10]

n-NONANE

Chemical formula: CH, (CH₂), CH₃

Molecular weight: 128.26

Normal boiling point: 423.97 K

Melting point: 219.7 K

Critical temperature: 594.63 K

Critical pressure: 2 289 kPa

Critical density: 234 kg/m³

T _{sat} , K	423.97	435	455	475	495	515	535	555	575	594.63	
p _{sat} , kPa	101.3	134	214	338	496	717	965	1 320	1750	2 289	[15, 76]
ρ _l , kg/m ³	614	602	581	560	535	510	479	444	394	234	[15]
ρ _g , kg/m ³	3.94	5.18	8.22	12.6	18.7	27.3	39.6	58.0	89.8	234	[62]
h _l , kJ/kg	195	226	282	340	402	464	529	594	664	754	[67]
h _g , kJ/kg	490	513	555	598	640	683	724	762	792	754	[63, 62, 691]
Δh _{g,l} , kJ/kg	295	287	273	258	238	219	195	168	128		[15]
c _{p,l} , kJ/(kg K)	2.72	2.77	2.87	2.97	3.10	3.23	3.38	3.59	4.00		[70]
c _{p,g} , kJ/(kg K)	2.24	2.30	2.40	2.51	2.63	2.77	2.95	3.25	4.05		[63, 62]
η _l , μNs/m ²	213	177	153	132	112	94	78	63	50		[1, 71]
η _g , μNs/m ²	7.4	7.6	7.9	8.3	8.7	9.1	9.7	10.6	12.2		[15, 14]
λ _l , W/(m·K)	95	92	87	82	77	72	66	60	55	49	[34, 68, 22]
λ _g , (mW/m ²)/(K/m)	20.8	22.0	24.1	26.4	28.7	31.2	33.8	36.6	40.0	49	[68, 22]
Pr _l	6.10	5.33	5.04	4.78	4.51	4.22	3.99	3.77	3.64		[12]
Pr _g	0.80	0.79	0.79	0.79	0.80	0.81	0.85	0.94	1.24		[12]
σ, mN/m	11.3	10.4	8.86	7.33	5.86	4.46	3.13	1.90	1.81		[23]
β _{e,l} , kK ⁻¹	1.60	1.71	1.94	2.27	2.70	3.33	4.36	6.31	11.7		[10]

n-DECANE

Chemical formula: CH, (CH₂), CH₃

Molecular weight: 142.3

Normal boiling point: 447.4 K

Melting point: 243.5 K

Critical temperature: 617.6 K

Critical pressure: 2 096 kPa

Critical density: 235.9 kg/m³

T _{sat} , K	447.31	460	480	500	520	540	560	580	600	617.6	
p _{sat} , kPa	101.3	141	227	329	479	675	927	1 250	1650	2 096	[15, 76]
ρ _l , kg/m ³	621	608	588	564	538	513	479	445	392	235.9	[15]
ρ _g , kg/m ³	4.13	5.60	8.73	13.2	19.4	28.1	40.7	59.6	93.1	235.9	[62]
h _l , kJ/kg	265	299	357	416	476	538	603	673	743	824	[67]
h _g , kJ/kg	542	569	613	658	702	746	789	829	859	824	[63, 62, 69]
Δh _{g,l} , kJ/kg	277	270	256	242	226	208	186	156	116		[15]
c _{p,l} , kJ/(kg K)	2.79	2.85	2.94	3.06	3.16	3.29	3.44	3.65	4.06		[70]
c _{p,g} , kJ/(kg K)	2.33	2.39	2.49	2.59	2.71	2.85	3.03	3.33	4.20		[63, 62]
η _l , μNs/m ²	205	180	149	127	108	91	75	61	48		[71, 33]
η _g , μNs/m ²	8.1	8.3	8.7	9.1	9.6	10.1	10.7	11.6	13.3		164, 141
λ _l , (mW/m ²)/(K/m)	91	88	83	78	73	68	63	58	54	49	[34, 68, 22]
λ _g , (mW/m ²)/(K/m)	21.8	23.1	25.3	27.5	29.8	32.1	34.7	37.5	40.9	49	[68, 22]
Pr _l	6.29	5.83	5.28	4.98	4.68	4.40	4.10	3.84	3.61		[12]
Pr _g	0.87	0.86	0.86	0.86	0.87	0.90	0.93	1.03	1.37		[12]
σ, mN/m	10.64	9.68	8.20	6.77	5.39	4.07	2.83	1.68	0.67		[23]
β _{e,l} , kK ⁻¹	1.61	1.70	1.99	2.30	2.71	3.41	4.58	6.60	12.8		[10]

CYCLOPENTANE

Chemical formula: $\text{CH}_2\langle(\text{CH}_2\text{CH}_2)_2\rangle$

Molecular weight: 70.135

Normal boiling point: 322.45 K

Melting point: 179.25 K

Critical temperature: 511.8 K

Critical pressure: 4 508 kPa

Critical density: 272 kg/m³

T_{sat} , K	322.4	350	370	390	410	430	450	470	490	511.8	
p_{sat} , kPa	101.3	239	406	642	948	1 309	1 861	2 742	3 562	4 508	1471
ρ_L , kg/m ³	706	680	656	635	607	577	547	505	455	272	1471
ρ_g , kg/m ³	10.8	20.0	36.3	52.1	69.2	97.5	117	141	176	272	[60]
h_L , kJ/kg	-288.7	-217.3	-179.4	-155.3	-92.8	-44.2	-3.8	62.2	127.4	227.1	[67]
h_g , kJ/kg	104.9	138.6	163.9	189.6	215.4	240.5	264.1	284.1	294.9	227.1	[63, 62, 691]
$\Delta h_{g,L}$, kJ/kg	393.6	355.9	343.3	334.9	318.2	284.7	267.9	221.9	167.5		[47]
$c_{p,L}$, kJ/(kg K)	1.92	2.05	2.12	2.22	2.37	2.53	2.73	3.04	3.78		[47, 71]
$c_{p,g}$, kJ/(kg K)	1.34	1.47	1.61	1.79	1.93	2.11	2.40	2.81	3.91		[47, 62]
η_L , $\mu\text{Ns/m}^2$	320	255	200	160	128	109	92	76	58	43	[47, 33]
η_g , $\mu\text{Ns/m}^2$	7.9	8.9	9.7	10.5	11.2	11.9	12.8	13.9	15.9	43	[47, 14]
λ_L , (mW/m ²)/(K/m)	125	117	111	105	98	91	85	79	68	51.1	[7]
λ_g , (mW/m ²)/(K/m)	16.3	18.5	20.8	23.2	25.7	28.4	31.3	34.8	39.0	51.1	[47, 22]
Pr_L	4.92	4.47	3.82	3.38	3.10	3.03	2.95	2.92	3.22		[12]
Pr_g	0.65	0.71	0.75	0.81	0.84	0.88	0.98	1.12	1.59		[12]
σ , mN/m	18.6	15.1	13.0	11.1	8.7	6.6	4.7	2.9	1.3		[47, 65]
$\beta_{e,L}$, kK^{-1}	1.49	1.75	1.99	2.30	2.73	3.36	4.36	6.22	11.05		[10]

CYCLOHEXANE

Chemical formula: $\text{CH}_2\langle(\text{CH}_2\text{CH}_2)_2\rangle\text{CH}_2$

Molecular weight: 84.132

Normal boiling point: 353.87 K

Melting point: 279.7 K

Critical temperature: 554.15 K

Critical pressure: 4 075 kPa

Critical density: 273 kg/m³

T_{sat} , K	353.87	360	385	410	435	460	485	510	535	554.15	
p_{sat} , kPa	101.3	124	234	414	689	1 069	1 586	2 275	3 723	4 075	[47]
ρ_L , kg/m ³	715	710	685	660	630	590	555	510	445	273	[47]
ρ_g , kg/m ³	3.02	3.75	6.76	11.6	18.9	29.0	42.9	64.6	144	273	[60]
h_L , kJ/kg	314.0	325.6	379.1	434.9	500.1	558.2	628.0	707.1	790.8	895.5	[15]
h_g , kJ/kg	674.2	681.34	717.2	751.9	791.5	820.44	859.8	902.1	933.0	895.5	[15]
$\Delta h_{g,L}$, kJ/kg	360.2	355.7	338.1	316.9	291.4	262.2	231.8	195.0	142.2		[47]
$c_{p,L}$, kJ/(kg K)	1.84	1.86	1.93	1.99	2.07	2.13	2.23	2.49	2.82		[5]
$c_{p,g}$, kJ/(kg K)	1.60	1.64	1.79	1.95	2.15	2.36	2.57	3.11	7.05		[63, 20]
η_L , $\mu\text{Ns/m}^2$	400	370	280	230	190	160	135	115	95.0	54.0	[87, 88]
η_g , $\mu\text{Ns/m}^2$	8.60	8.71	9.44	10.18	10.72	11.58	12.33	13.56	17.73	54.0	[43]
λ_L , (mW/m ²)/(K/m)	102	100	92.6	86.5	77.9	69.2	60.6	56.5	48.3	57.9	134,251
λ_g , (mW/m ²)/(K/m)	16.5	17.4	20.1	22.9	26.0	30.4	36.1	39.4	45.9	57.9	[86]
Pr_L	7.21	6.88	5.83	5.29	5.05	4.92	4.96	5.07	5.55		[12]
Pr_g	0.83	0.82	0.84	0.87	0.87	0.90	0.88	1.07	2.72		[12]
σ , mN/m	18.0	17.2	13.0	11.0	8.1	5.2	2.0	1.5	0.5		[89]
$\beta_{e,L}$, kK^{-1}	1.10	1.30	1.48	1.70	2.31	2.50	3.05	4.89	15.8		[10]

BENZENE

Chemical formula: C_6H_6
 Molecular weight: 78.108
 Normal boiling point: 353.25 K
 Melting point: 278.7 K

Critical temperature: 562.6 K
 Critical pressure: 4 924 kPa
 Critical density: 301.6 kg/m³

T_{sat}, K	353.3	375	400	425	450	475	500	525	550	562.6	
p_{sat}, kPa	101.3	191	354	607	975	1484	2 166	3 060	4 218	4 924	[1]
$\rho_L, kg/m^3$	823	798	767	735	699	660	615	559	475	304	[1]
$\rho_g, kg/m^3$	2.74	4.90	8.87	14.8	23.6	36.1	54.2	82.0	133	304	[1]
$h_L, kJ/kg$	-154.3	-113.0	-62.1	-8.9	47.5	106.8	169.7	238.6	322.8	432.6	[1]
$h_g, kJ/kg$	243.4	270.3	302.1	334.8	367.9	400.7	432.3	460.4	478.5	432.6	[1]
$\Delta h_{fg}, kJ/kg$	397.7	383.3	364.2	343.7	320.4	293.9	262.6	221.8	155.7		[1]
$c_{p,L}, kJ/(kg K)$	1.88	1.98	2.08	2.20	2.32	2.45	2.60	2.83			[1]
$c_{p,g}, kJ/(kg K)$	1.29	1.40	1.53	1.67	1.81	2.01	2.32	2.73			[4, 20]
$\eta_L, \mu Ns/m^2$	321	258	205	166	138	116	97.9	80.7	59.6		[1]
$\eta_g, \mu Ns/m^2$	9.26	9.87	10.7	11.5	12.5	13.7	15.0	16.8	19.1		[1]
$\lambda_L, (mW/m^2)/(K/m)$	131	126	119	112	106	100	93.5	87.1	77.4	62.6	[2]
$\lambda_g, (mW/m^2)/(K/m)$	14.8	17.1	19.8	23.0	26.7	31.0	35.7	41.1	50.2	62.6	[2, 22]
Pr_L	4.61	4.05	3.58	3.26	3.02	2.84	2.75	2.62			[12]
Pr_g	0.81	0.82	0.83	0.84	0.85	0.89	0.97	1.12			[12]
$\sigma, mN/m$	21.2	18.5	15.5	12.7	9.89	7.26	4.80	2.55	0.65		[6]
$\beta_{e,L}, kK^{-1}$	1.15	1.37	1.67	2.02	2.49	3.13	4.32	6.98	16.0		[10]

TOLUENE

Chemical formula: $C_6H_5CH_3$
 Molecular weight: 92.134
 Normal boiling point: 383.78 K
 Melting point: 178.16 K

Critical temperature: 594.0 K
 Critical pressure: 4 050 kPa
 Critical density: 290 kg/m

T_{sat}, K	383.78	400	425	450	475	500	525	550	575	594.0	
p_{sat}, kPa	101.3	158	285	487	776	1 230	1820	2570	3 450	4 050	[1]
$\rho_L, kg/m^3$	778	760	733	702	670	632	590	541	469	290	[1, 77]
$\rho_g, kg/m^3$	2.91	4.42	7.88	13.2	20.9	32.2	48.8	74.3	120.8	290	[62]
$h_L, kJ/kg$	695	725	762	797	832	866	901	932	948	899	[15]
$h_g, kJ/kg$	336	381	432	488	551	604	667	734	808	899	[15]
$\Delta h_{fg}, kJ/kg$	359	344	330	309	281	262	234	198	140		[15]
$c_{p,L}, kJ/(kg K)$	1.81	1.88	1.96	2.07	2.21	2.38	2.59	2.86	3.34		[5]
$c_{p,g}, kJ/(kg K)$	1.13	1.18	1.25	1.33	1.42	1.54	1.71	2.04	3.33		[63, 62]
$\eta_L, \mu Ns/m^2$	251	220	183	153	134	118	104	92	82	50	[1, 25]
$\eta_g, \mu Ns/m^2$	9.0	9.5	10.1	10.7	11.4	12.5	13.7	15.0	17.2	50	[1, 14]
$\lambda_L, (mW/m^2)/(K/m)$	111.3	108	103	98	92	86	79	72	65	37.8	[1, 7]
$\lambda_g, (mW/m^2)/(K/m)$	11.1	12.3	14.2	16.0	17.8	19.8	21.9	24.4	27.8	37.8	[64, 22]
Pr_L	4.02	3.83	3.48	3.23	3.22	3.27	3.41	3.65	4.21		[12]
Pr_g	0.92	0.91	0.89	0.89	0.91	0.97	1.07	1.25	2.06		[12]
$\sigma, mN/m$	18.0	16.3	13.8	11.4	8.99	6.74	4.62	2.66	0.95		[65]
$\beta_{e,L}, kK^{-1}$	1.38	1.43	1.67	2.07	2.52	3.11	3.98	6.15	14.3		[10]

m-XYLENEChemical formula: $C_6H_4(CH_3)_2$

Molecular weight: 106.168

Normal boiling point: 412.3 K

Melting point: 225.5 K

Critical temperature: 617.0 K

Critical pressure: 3 543 kPa

Critical density: 283 kg/m

T_{sat}, K	412	430	455	480	505	530	555	580	605	617	
p_{sat}, kPa	101.3	162	281	472	741	1 121	1601	2 264	3 052	3 543	[1, 15]
$\rho_l, kg/m^3$	752	731	700	673	642	604	570	505	396	283	[47]
$\rho_g, kg/m^3$	3.22	4.98	8.69	14.3	22.6	34.6	52.6	81.3	140	283	[62]
$h_l, kJ/kg$	-34.6	-1.2	50.2	114.7	172.6	233.9	299.2	371.4	460.6	516.7	[67]
$h_g, kJ/kg$	310.8	337.9	376.8	416.1	455.2	493.5	529.5	559.8	571.1	516.7	[63, 62, 69]
$\Delta h_{g,l}, kJ/kg$	345.4	339.1	326.6	301.4	282.6	259.6	230.3	188.4	100.5		[47]
$c_{p,l}, kJ/(kg K)$	2.13	2.19	2.29	2.40	2.54	2.69	2.87	3.16	3.86		1701
$c_{p,g}, kJ/(kg K)$	1.66	1.73	1.84	1.95	2.08	2.24	2.47	2.91	5.27		163,621
$\eta_l, \mu Ns/m^2$	232	207	182	158	135	112	90	71	55	54	147,331
$\eta_g, \mu Ns/m^2$	9.1	9.5	10.0	10.7	11.4	12.2	13.2	14.6	18.3	54	[47, 14]
$\lambda_l, (mW/m^2)/(K/m)$	92	88	82	77	72	67	62	57	52	50	[47, 34]
$\lambda_g, (mW/m^2)/(K/m)$	16.9	19.4	22.1	24.6	27.2	29.9	33.1	37.1	42.2	50	147,221
Pr_l	5.38	5.18	5.08	4.92	4.76	4.54	4.17	3.94	4.08		[12]
Pr_g	0.89	0.85	0.83	0.85	0.87	0.91	0.99	1.15	2.29		[12]
$\sigma, mN/m$	16.7	14.8	12.5	10.2	8.0	5.9	3.9	2.1	0.5		[47, 65]
$\beta_{e,l}, K^{-1}$	1.38	1.50	1.73	2.04	2.47	3.14	4.29	6.83	18.0		[10]

o-XYLENEChemical formula: $C_6H_4(CH_3)_2$

Molecular weight: 106.168

Normal boiling point: 417.6 K

Melting point: 248.0 K

Critical temperature: 630.4 K

Critical pressure: 3 729 kPa

Critical density: 288 kg/m³

T_{sat}, K	417.56	430	455	480	505	530	555	580	605	630.4	
p_{sat}, kPa	101.3	142	249	422	655	995	1420	2 040	2 750	3 729	[1, 15]
$\rho_l, kg/m^3$	764	751	725	696	666	632	594	549	489	288	[47]
$\rho_g, kg/m^3$	3.17	4.31	7.54	12.5	19.6	30.0	45.1	67.8	107	288	[62]
$h_l, kJ/kg$	6.5	30.4	83.2	145.0	201.7	263.7	331.0	400.6	476.9	581.2	[67]
$h_g, kJ/kg$	349.9	369.5	409.8	450.5	491.4	531.7	570.5	605.8	631.8	581.2	[66, 62, 69]
$\Delta h_{g,l}, kJ/kg$	343.4	339.1	326.6	305.5	289.7	268.0	239.5	205.2	154.9		[47]
$c_{p,l}, kJ/(kg K)$	2.16	2.20	2.30	2.40	2.52	2.65	2.81	3.02	3.44		[70]
$c_{p,g}, kJ/(kg K)$	1.71	1.76	1.86	1.97	2.08	2.22	2.40	2.70	3.49		[63, 62]
$\eta_l, \mu Ns/m^2$	253	231	197	171	147	124	102	82	65	55	[47, 33]
$\eta_g, \mu Ns/m^2$	9.2	9.5	10.2	10.8	11.5	12.2	13.1	14.3	16.3	55	[47, 14]
$\lambda_l, (mW/m^2)/(K/m)$	99	96	91	85	80	74	69	63	58	52	[47, 34]
$\lambda_g, (mW/m^2)/(K/m)$	18.4	19.3	21.9	24.4	27.0	29.9	33.0	36.5	40.6	52	[47, 22]
Pr_l	5.51	5.28	5.00	4.83	4.65	4.43	4.14	3.92	3.87		[12]
Pr_g	0.86	0.87	0.87	0.88	0.89	0.91	0.95	1.06	1.40		[12]
$\sigma, mN/m$	17.9	16.4	14.1	11.4	9.2	7.0	4.9	3.0	1.3		[47, 65]
$\beta_{e,l}, K^{-1}$	1.31	1.39	1.59	1.85	2.20	2.71	3.54	5.11	9.36		[10]

p-XYLENEChemical formula: $C_6H_4(CH_3)_2$

Molecular weight: 106.168

Normal boiling point : 4 11.5 K

Melting point: 286.4 K

Critical temperature: 616.3 K

Critical pressure: 3 510 kPa

Critical density: 280 kg/m³

T_{sat}, K	412	430	455	480	505	530	555	580	605	618	
p_{sat}, kPa	101.3	161	287	476	752	1 120	1590	2 270	3 100	3 510	[1]
$\rho_L, kg/m^3$	753	734	706	676	643	607	565	513	432	280	[47]
$\rho_g, kg/m^3$	3.23	5.08	8.83	14.5	22.8	34.9	52.9	81.8	142	280	[62]
$h_L, kJ/kg$	-35.7	-2.4	49.7	113.8	171.4	232.3	297.2	368.9	466.7	514.0	1671
$h_g, kJ/kg$	309.7	337.7	376.3	415.2	454.0	491.9	527.5	557.3	567.2	514.0	[63, 62, 691]
$\Delta h_{g,L}, kJ/kg$	345.4	339.1	326.6	301.4	282.6	259.6	230.3	188.4	100.5		[47]
$c_{p,L}, kJ/(kg K)$	2.11	2.18	2.27	2.39	2.52	2.67	2.86	3.15	3.88		147,701
$c_{p,g}, kJ/(kg K)$	1.64	1.72	1.83	1.94	2.07	2.23	2.46	2.92	5.51		[63, 62]
$\eta_L, \mu Ns/m^2$	232	205	176	155	132	109	89	70	54	53	[47, 33]
$\eta_g, \mu Ns/m^2$	8.8	9.5	10.1	10.7	11.4	12.2	13.1	14.6	18.0	53	(47,141
$\lambda_L, (mW/m^2)/(K/m)$	98	93	87	81	75	69	63	57	52	49	147,341
$\lambda_g, (mW/m^2)/(K/m)$	17.1	19.7	22.1	24.6	27.2	30.0	33.0	37.1	42.3	49	[47, 22]
Pr_L	5.00	4.81	4.59	4.57	4.44	4.22	4.04	3.87	4.03		[12]
Pr_g	0.84	1.83	0.84	0.84	0.87	0.91	0.98	1.15	2.34		[12]
$\sigma, mN/m$	16.0	14.2	11.8	10.0	7.8	5.7	3.8	2.0	0.5		[47, 65]
$\beta_{e,L}, kK^{-1}$	1.57	1.74	1.83	1.97	2.62	3.03	4.87	12.3	42.7		[10]

ETHYL BENZENEChemical formula: $C_6H_5 \bullet C_2H_5$

Molecular weight: 106.2

Normal boiling point: 409.3 K

Melting point: 178.1 K

Critical temperature: 617.1 K

Critical pressure: 3 610 kPa

Critical density: 284 kg/m³

T_{sat}, K	409.3	433	453	473	493	513	553	573	593	613	
p_{sat}, kPa	101.3	189	297	447	645	903	1640	2 150	2 770	3 450	[15]
$\rho_L, kg/m^3$	751	727	705	682	657	630	568	529	478	388	[15]
$\rho_g, kg/m^3$	3.26	5.76	8.88	13.2	19.0	26.9	52.1	72.9	106	189	[62]
$h_L, kJ/kg$	-42.8	9.0	53.3	101.6	159.3	207.9	306.7	368.2	427.8	481.6	[67]
$h_g, kJ/kg$	298.8	335.6	367.3	399.3	431.4	463.3	524.4	550.8	570.2	557.0	[63, 62, 691]
$\Delta h_{g,L}, kJ/kg$	341.6	326.6	314.0	297.7	272.1	255.4	217.7	192.6	142.4	75.4	[66]
$c_{p,L}, kJ/(kg K)$	1.98	2.04	2.11	2.19	2.28	2.38	2.63	2.85	3.22	4.20	[5]
$c_{p,g}, kJ/(kg K)$	1.67	1.77	1.86	1.95	2.05	2.16	2.48	2.78	3.52	17.5	[63, 62]
$\eta_L, \mu Ns/m^2$	230	197	176	158	142	129	108	99	91	84	[25]
$\eta_g, \mu Ns/m^2$	9.0	9.6	10.3	11.0	11.7	12.4	13.7	14.8	16.6	22.6	[26, 14]
$\lambda_L, (mW/m^2)/(K/m)$	99	95	90	85	80	75	65	60	55	50	[7]
$\lambda_g, (mW/m^2)/(K/m)$	16.9	19.4	21.5	23.6	25.9	28.2	33.2	36.1	39.5	45.8	[68, 22]
Pr_L	4.60	4.31	4.13	4.07	4.05	4.09	4.37	4.70	5.32	7.02	[12]
Pr_g	0.87	0.88	0.89	0.91	0.93	0.95	1.02	1.14	1.48	8.64	[12]
$\sigma, mN/m$	16.6	14.5	12.5	10.5	8.8	7.1	3.9	2.5	1.2	0.23	[6]
$\beta_{e,L}, kK^{-1}$	1.35	1.52	1.70	1.93	2.23	2.64	4.14	5.80	9.88		[10]

ACETYLENE

Chemical formula: $\text{HC}\equiv\text{CH}$
 Molecular weight: 26.036
 Normal boiling point: 189.2 K
 Melting point: 192.2 K

Critical temperature: 308.7 K
 Critical pressure: 6 240 kPa
 Critical density: 230 kg/m^3

T_{sat}, K	192.2	200	210	230	240	250	270	280	290	308.7	
$p_{\text{sat}}, \text{kPa}$	128	189	304	689	986	1 370	2 450	3 190	4 080	6 240	[9]
$\rho_{\ell}, \text{kg/m}^3$	617	606	590	556	538	519	473	445	411	231	[9]
$\rho_g, \text{kg/m}^3$	2.16	3.11	4.86	10.8	15.6	22.1	41.0	54.0	73.2	231	[9]
$h_{\ell}, \text{kJ/kg}$	-369.5	-351.8	-331.6	-271.6	-236.1	-202.0	-136.2	-100.5	-66.2	104.7	[9]
$h_g, \text{kJ/kg}$	214.8	222.9	230.9	248.6	254.4	257.6	257.0	252.8	238.8	104.7	[9]
$\Delta h_{g,\ell}, \text{kJ/kg}$	584.3	574.7	562.5	520.2	490.5	459.6	393.2	363.3	305.0		[9]
$c_{p,\ell}, \text{kJ/(kg K)}$	3.09	3.12	3.15	3.27	3.35	3.46	3.87	4.25	5.14		[13, 24]
$c_{p,g}, \text{kJ/(kg K)}$	1.47	1.51	1.59	1.80	1.93	2.14	2.64	2.93	3.39		[9]
$\eta_{\ell}, \mu\text{Ns/m}^2$	169	156	146	127	116	99.6	79.9	66.9	56.9		[32, 33]
$\eta_g, \mu\text{Ns/m}^2$	7.35	7.67	8.10	8.68	9.03	9.44	10.5	11.2	12.1		[38, 14]
$\lambda_{\ell}, (\text{mW/m}^2)/(\text{K/m})$	55.9	54.3	51.9	48.0	48.3	44.9	43.0	42.2	41.5		[34, 35]
$\lambda_g, (\text{mW/m}^2)/(\text{K/m})$	11.2	12.0	13.1	15.4	16.9	18.5	22.6	25.0	28.3		[3, 22]
Pr_{ℓ}	9.34	8.96	8.86	8.65	8.39	7.68	7.19	6.75	7.04		[12]
Pr_g	0.96	0.97	0.98	1.01	1.03	1.09	1.23	1.31	1.45		[12]
$\sigma, \text{mN/m}$	19.1	17.6	15.6	11.8	9.92	8.12	4.64	3.11	1.73		[27, 28]
$\beta_{e,\ell}, \text{K}^{-1}$	2.21	2.45	2.79	3.56	4.02	4.73	7.28	8.97	15.6		[29]

ETHYLENE

Chemical formula: $\text{H}_2\text{C}=\text{CH}_2$
 Molecular weight: 28.052
 Normal boiling point: 169.43 K
 Melting point: 104 K

Critical temperature: 282.65 K
 Critical pressure: 5 060 kPa
 Critical density: 220 kg/m^3

T_{sat}, K	169.43	183	193	203	213	223	233	243	263	281	
$p_{\text{sat}}, \text{kPa}$	101.3	213	341	518	755	1 063	1453	1938	3 240	4899	[9]
$\rho_{\ell}, \text{kg/m}^3$	567.92	547.95	532.88	517.17	500.61	482.84	463.41	441.61	385.64	287.43	[9]
$\rho_g, \text{kg/m}^3$	2.09	4.24	6.60	9.81	14.01	19.47	26.58	36.12	69.58	152.70	[9]
$h_{\ell}, \text{kJ/kg}$	-662.49	-624.50	-600.49	-578.48	-552.50	-526.51	-498.48	-468.50	-396.51	-301.15	[9]
$h_g, \text{kJ/kg}$	-179.97	-163.61	-155.64	-151.12	-145.06	-141.54	-140.04	-140.71	-152.62	-213.38	[9]
$\Delta h_{g,\ell}, \text{kJ/kg}$	482.52	460.89	444.85	427.36	407.44	384.97	358.44	327.79	243.89	94.56	[9]
$c_{p,\ell}, \text{kJ/(kg K)}$	2.32	2.46	2.54	2.61	2.67	2.73	2.80	2.93	3.89		[9]
$c_{p,g}, \text{kJ/(kg K)}$	1.31	1.35	1.40	1.47	1.56	1.67	1.82	2.02	2.91		191
$\eta_{\ell}, \mu\text{Ns/m}^2$	162.0	138.5	124.1	112.1	102.6	94.4	86.4	77.6	55.9	28.7	[4]
$\eta_g, \mu\text{Ns/m}^2$	6.04	6.56	6.96	7.37	7.81	8.29	9.82	9.44	11.30	16.25	[9]
$\lambda_{\ell}, (\text{mW/m}^2)/(\text{K/m})$	192	178	168	158	147	137	126	116	94.7	77.0	[2]
$\lambda_g, (\text{mW/m}^2)/(\text{K/m})$	6.44	7.62	8.62	9.71	11.0	12.4	14.0	15.9	21.9		[9]
Pr_{ℓ}	1.96	1.91	1.88	1.85	1.86	1.88	1.92	1.96	2.30		[12]
Pr_g	1.23	1.16	1.13	1.11	1.10	1.11	1.14	1.20	1.50		[12]
$\sigma, \text{mN/m}$	16.46	13.99	12.23	10.52	8.88	7.29	5.78	4.35	1.80	0.16	[6]
$\beta_{e,\ell}, \text{K}^{-1}$	2.52	2.83	3.12	3.47	3.88	4.50	5.40	6.70	10.4		[10]

PROPYLENE

Chemical formula: $\text{CH}_3\text{CH}:\text{CH}_2$

Molecular weight: 42.078

Normal boiling point: 225.45 K

Melting point: 87.9 K

Critical temperature: 364.8 K

Critical pressure: 4 610 kPa

Critical density: 233 kg/m^3

T_{sat} , K	225.45	240	255	270	285	300	315	330	345	365	
p_{sat} , kPa	101.3	187	333	530	820	1 210	1710	2410	3190	4610	[1]
ρ_L , kg/m^3	611	587	575	556	535	509	481	443	390	233	[46]
ρ_g , kg/m^3	2.15	3.93	6.68	10.70	16.4	24.4	35.6	51.7	77.2	233	[62]
h_L , kJ/kg	-309.0	-273.7	-237.3	-199.8	-161.2	-121.3	-79.8	-36.2	10.4	119.5	[67]
h_g , kJ/kg	130.2	150.0	164.8	182.3	196.3	212.0	229.7	220.2	210.5	119.5	[46, 62, 69]
$\Delta h_{g,L}$, kJ/kg	439.2	423.7	402.1	382.1	357.5	333.3	309.5	256.4	220.9		[1]
$c_{p,L}$, kJ/(kg K)	2.39	2.45	2.55	2.64	2.72	2.85	3.10	3.40	3.77		[46]
$c_{p,g}$, kJ/(kg K)	1.31	1.40	1.49	1.62	1.78	1.96	2.23	2.62	3.71		[46]
η_L , $\mu\text{Ns/m}^2$	151	132	108	101	99.2	90.3	80.9	78.7	61.1	32	[46]
η_g , $\mu\text{Ns/m}^2$	6.62	7.14	7.53	8.04	8.74	9.26	10.1	11.4	12.7	32	[46]
λ_L , (mW/m ²)/(K/m)	119	111	104	98.6	93.6	90.9	88.0	83.3	76.1	49.3	[34]
λ_g , (mW/m ²)/(K/m)	9.52	11.2	13.0	14.9	17.1	19.4	22.2	25.4	29.6	49.3	[68, 22]
Pr_L	3.03	2.91	2.65	2.70	2.88	2.83	2.85	3.21	3.03		[12]
Pr_g	0.91	0.89	0.86	0.87	0.91	0.94	1.01	1.18	1.69		[12]
σ , mN/m	16.5	14.7	12.6	10.5	8.7	6.5	5.1	3.4	2.0		[46]
$\beta_{e,L}$, K^{-1}	1.99	2.22	2.52	2.90	3.42	4.17	5.32	7.38	12.2		[10]

1,2-BUTADIENE

Chemical formula: $\text{CH}_3\text{CH}:\text{C}:\text{CH}_2$

Molecular weight: 54.09

Normal boiling point: 284.0 K

Melting point: 137.0 K

Critical temperature: 443.7 K

Critical pressure: 4 500 kPa

Critical density: 246.8 kg/m^3

T_{sat} , K	284.0	300	315	330	345	360	375	390	400	443.7	
p_{sat} , kPa	101.3	189	265	445	661	945	1310	1770	2140	4500	[46, 76]
ρ_L , kg/m^3	651	643	625	605	585	563	537	507	485	246.8	[46]
ρ_g , kg/m^3	2.32	4.04	6.43	9.80	14.4	20.7	29.2	40.7	50.8	246.8	[62]
h_L , kJ/kg	-197	-166	-131	-94	-57	-19	19	61	88	255	[67]
h_g , kJ/kg	237	257	275	293	311	327	341	354	359	255	[46, 62, 69]
$\Delta h_{g,L}$, kJ/kg	434	423	406	387	368	346	322	293	271		[46]
$c_{p,L}$, kJ/(kg K)	2.20	2.24	2.30	2.41	2.49	2.60	2.72	2.87	3.01		[46]
$c_{p,g}$, kJ/(kg K)	1.48	1.56	1.65	1.75	1.87	2.01	2.18	2.43	2.68		[46, 62]
η_L , $\mu\text{Ns/m}^2$	200	185	170	150	134	116	100	85	76	43	[46, 33]
η_g , $\mu\text{Ns/m}^2$	7.40	7.78	8.27	8.76	9.26	9.77	10.4	11.0	11.5	43	[46, 14]
λ_L , (mW/m ²)/(K/m)	126	119	113	107	102	98	93	88	82	49	[34]
λ_g , (mW/m ²)/(K/m)	12.5	14.1	15.8	17.5	19.3	21.2	23.3	25.6	27.3	49	[68, 22]
Pr_L	3.62	3.48	3.46	3.38	3.27	3.08	2.92	2.77	2.79		[12]
Pr_g	0.88	0.86	0.86	0.88	0.90	0.93	0.97	1.04	1.13		[12]
σ , mN/m	18.0	15.7	13.9	12.1	10.4	8.65	7.00	5.30	4.10		[46]
$\beta_{e,L}$, K^{-1}	1.71	1.89	2.10	2.35	2.66	3.77	4.11	4.85	5.74		[10]

1,3-BUTADIENEChemical formula: CH₂:CHCH:CH₂

Molecular weight: 54.088

Normal boiling point: 268.69 K

Melting point: 164.24 K

Critical temperature: 425.15 K

Critical pressure: 4 330 kPa

Critical density: 245 kg/m³

T_{sat}, K	268.69	285	300	315	330	350	370	390	410	425.15	
$p_{\text{sat}}, \text{kPa}$	101.3	184	298	458	676	1 080	1 630	2370	3350	4330	[1]
$\rho_{\text{L}}, \text{kg/m}^3$	650	631	612	593	572	541	507	464	405	245	[1]
$\rho_{\text{g}}, \text{kg/m}^3$	2.53	4.41	6.97	10.5	15.5	26.7	38.7	53.5	101	245	[1]
$h_{\text{L}}, \text{kJ/kg}$	493.3	529.0	563.0	598.4	635.0	686.5	741.5	800.1	867.5		[1]
$h_{\text{g}}, \text{kJ/kg}$	908.7	928.4	946.4	964.4	981.7	1003.8	1023.2	1038.3	1041.4		[1]
$\Delta h_{\text{g,L}}, \text{kJ/kg}$	415.4	399.4	383.4	366.0	346.7	317.3	281.7	238.2	173.9		[1]
$c_{p,\text{L}}, \text{kJ/(kg K)}$	2.14	2.22	2.29	2.37	2.47	2.63	2.81	3.03	3.28		[1, 5]
$c_{p,\text{g}}, \text{kJ/(kg K)}$	1.42	1.53	1.63	1.74	1.87	2.07	2.35	2.92	4.54		[30, 20]
$\eta_{\text{L}}, \mu\text{Ns/m}^2$	200	164	138	117	99.5	84.3	71.3	61.7	53.4		[1, 25]
$\eta_{\text{g}}, \mu\text{Ns/m}^2$	7.57	8.43	8.91	9.41	9.94	10.7	11.6	12.6	15.0		[26, 14]
$\lambda_{\text{L}}, (\text{mW/m}^2)/(\text{K/m})$	126	117	110	103	95.6	86.6	78.0	69.8	62.0	53.7	[7]
$\lambda_{\text{g}}, (\text{mW/m}^2)/(\text{K/m})$	9.54	12.3	14.7	17.3	19.9	23.7	21.5	31.6	37.8	53.7	[31, 22]
Pr_{L}	3.40	3.11	2.87	2.69	2.57	2.56	2.57	2.68	2.83		[12]
Pr_{g}	1.13	1.05	0.99	0.95	0.93	0.93	1.02	1.16	1.30		[12]
$\sigma, \text{mN/m}$	16.6	14.5	12.7	10.9	9.12	6.86	4.73	2.15	1.00		[6]
$\beta_{e,\text{L}}, \text{K}^{-1}$	1.79	1.98	2.20	2.45	2.84	3.57	4.88	7.64	20.0		[10]

METHANOLChemical formula: CH₃ OH

Molecular weight: 32.00

Normal boiling point: 337.85 K

Melting point: 175.15 K

Critical temperature: 513.15 K

Critical pressure: 7 950 kPa

Critical density: 275 kg/m³

T_{sat}, K	331.85	353.2	373.2	393.2	413.2	433.2	453.2	473.2	493.2	511.7	
$p_{\text{sat}}, \text{kPa}$	101.3	118.4	349.4	633.3	1076	1 736	2 678	3 970	5 675	1175	[1]
$\rho_{\text{L}}, \text{kg/m}^3$	751.0	735.5	714.0	690.0	664.0	634.0	598.0	553.0	490.0	363.5	[1]
$\rho_{\text{g}}, \text{kg/m}^3$	1.222	2.084	3.984	7.142	12.16	19.94	31.86	50.75	86.35	178.9	[1]
$h_{\text{L}}, \text{kJ/kg}$	0.0	45	108	176	249	328	413	506			[84]
$h_{\text{g}}, \text{kJ/kg}$	1 101	1115	1 130	1 144	1171	1 171	1 169	1151			[104]
$\Delta h_{\text{g,L}}, \text{kJ/kg}$	1 101	1070	1022	968	922	843	756	645	482		[105]
$c_{p,\text{L}}, \text{kJ/(kg K)}$	2.88	3.03	3.26	3.52	3.80	4.11	4.45	4.81			[6]
$c_{p,\text{g}}, \text{kJ/(kg K)}$	1.55	1.61	1.69	1.83	1.99	2.20	2.56	3.65	5.40		[3]
$\eta_{\text{L}}, \mu\text{Ns/m}^2$	326	271	214	170	136	109	88.3	71.6	58.3	41.6	[1, 20, 106]
$\eta_{\text{g}}, \mu\text{Ns/m}^2$	11.1	11.6	12.4	13.1	14.0	14.9	16.0	17.4	20.1	26.0	[4, 21]
$\lambda_{\text{L}}, (\text{mW/m}^2)/(\text{K/m})$	191.4	187.0	181.3	178.5	170.0	164.0	158.7	153.0	147.3	142.0	[2]
$\lambda_{\text{g}}, (\text{mW/m}^2)/(\text{K/m})$	18.3	20.6	23.2	26.2	29.7	33.8	39.4	46.9	60.0	98.7	[2, 22, 107]
Pr_{L}	5.13	4.67	4.15	3.61	3.34	2.82	2.56	2.42			[12]
Pr_{g}	0.94	0.91	0.90	0.92	0.94	0.97	1.04	1.35	1.81		[12]
$\sigma, \text{mN/m}$	18.75	17.5	15.7	13.6	11.5	9.3	6.9	4.5	2.1	0.09	[1]
$\beta_{e,\text{L}}, \text{K}^{-1}$	0.42	1.20	1.69	2.00	2.49	3.15	4.21	6.40	17.2		[10]

ETHANOLChemical formula: **CH₃CH₂OH**

Molecular weight: 46.1

Normal boiling point: 351.45 K

Melting point: 158.65 K

Critical temperature: 516.25 K

Critical pressure: 6 390 kPa

Critical density: 280 kg/m³

T_{sat}, K	351.45	373	393	413	433	453	473	483	503	513	
p_{sat}, kPa	101.3	226	429	753	1 256	1960	2 940	3 560	5 100	6 020	[1]
ρ_l, kg/m³	757.0	733.7	709.0	680.3	648.5	610.5	564.0	537.6	466.2	420.3	[1]
ρ_g, kg/m³	1.435	3.175	5.841	10.25	17.15	27.65	44.40	56.85	101.1	160.2	[1, 62]
h_l, kJ/kg	202.5	271.7	340.0	413.2	491.5	576.5	670.7	722.2	837.4	909.8	[1]
h_g, kJ/kg	1165.5	1198.7	1225.5	1247.2	1264.4	1215.3	1269.0	1259.0	1 224.6	1 190.3	[1]
Δh_{g,l}, kJ/kg	963.0	927.0	885.5	834.0	772.9	698.9	598.3	536.7	387.3	280.5	[1]
c_{p,l}, kJ/(kg K)	3.00	3.30	3.61	3.96	4.65	5.51	6.16	6.61			[1, 5]
c_{p,g}, kJ/(kg K)	1.83	1.92	2.02	2.11	2.31	2.80	3.18	3.78	6.55		[3, 20, 106]
η_l, μNs/m²	428.7	314.3	240.0	185.5	144.6	113.6	89.6	79.7	63.2	56.3	[25]
η_g, μNs/m²	10.4	11.1	11.7	12.3	12.9	13.7	14.5	15.1	16.7	18.5	[1, 21]
λ_l, (mW/m²)/(K/m)	153.6	150.7	146.5	141.9	137.2	134.8	129.1	125.6	108.0	79.11	[3]
λ_g, (mW/m²)/(K/m)	19.9	22.4	24.5	26.8	29.3	32.1	35.3	37.8	43.9	50.7	[2, 22, 107]
Pr_l	8.37	6.88	5.91	5.18	4.90	4.64	4.28	4.19			[12]
Pr_g	0.96	0.95	0.96	0.97	1.02	1.20	1.31	1.51	2.49		[12]
σ, mN/m	17.7	15.7	13.6	11.5	9.3	6.9	4.5	3.3	0.9	0.34	[1]
β_{e,l}, kK⁻¹	1.41	1.60	1.90	2.41	3.13	4.18	6.06	7.56	16.0		[10]

1-PROPANOLChemical formula: CH₃CH₂CH₂OH

Molecular weight: 60.1

Normal boiling point: 370.95 K

Melting point: 184.15 K

Critical temperature: 536.85 K

Critical pressure: 5 050 kPa

Critical density: 273 kg/m³

T_{sat}, K	373.2	393.2	413.2	433.2	453.2	473.2	493.2	513.2	523.2	533.1	
p_{sat}, kPa	109.4	218.5	399.2	683.6	1 089	1 662	2 426	3 402	3 998	4 689	[1]
ρ_l, kg/m³	732.5	711	687.5	660	628.5	592.0	548.5	492.0	452.5	390.5	[1]
ρ_g, kg/m³	2.26	4.43	8.05	13.8	22.5	35.3	55.6	90.4	118.0	161.0	[1]
h_l, kJ/kg	0.0	65	139	222	315	433	548	691			[84]
h_g, kJ/kg	687	710	733	766	802	860	904	955			[104]
Δh_{g,l}, kJ/kg	687	645	594	544	486	427	356	264	209	138	[1]
c_{p,l}, kJ/(kg K)	3.21	3.47	3.86	4.36	5.02	5.90	6.78	7.79			[6]
c_{p,g}, kJ/(kg K)	1.65	1.82	1.93	2.05	2.20	2.36	2.97	3.94			[5, 20, 106]
η_l, μNs/m²	447	337	250	188	148	119	90.6	70.0	61.4	53.9	[1, 7]
η_g, μNs/m²	9.61	10.3	10.9	11.5	12.2	12.9	14.2	15.7	17.0	19.3	[7, 21]
λ_l, (mW/m²)/(K/m)	142.4	139.2	138.4	133.5	127.9	120.7	111.8	100.6	94.1	89.3	[6]
λ_g, (mW/m²)/(K/m)	20.9	23.0	26.2	28.9	31.4	34.7	38.0	43.9	47.5	53.5	[7, 22, 107]
Pr_l	10.1	8.40	6.97	5.14	5.81	5.82	5.50	5.42			[12]
Pr_g	0.76	0.82	0.80	0.82	0.85	0.88	1.11	1.41			[12]
σ, mN/m	17.6	16.15	14.42	12.7	10.77	8.85	6.35	4.04	2.6	0.96	[6]
β_{e,l}, kK⁻¹	1.33	1.57	1.91	2.43	3.15	4.14	5.82	9.19	13.6		[10]

2-PROPANOLChemical formula: $(\text{CH}_3)_2\text{CHOH}$

Molecular weight: 60.1

Normal boiling point: 355.65 K

Melting point: 194.15 K

Critical temperature: 508.75 K

Critical pressure: **5 370 kPa**Critical density: 274 kg/m³

T_{sat}, K	355.65	373	390	408	425	443	459	478	498	508	
$p_{\text{sat}}, \text{kPa}$	101.3	200	380	580	925	1 425	2 025	3 039	4 052	5 369	[1, 18]
$\rho_{\ell}, \text{kg/m}^3$	732.3	712.7	683.0	660.0	630.1	597.4	566.0	514.8	460.5	288.0	[1, 18]
$\rho_g, \text{kg/m}^3$	2.06	4.15	7.73	14.3	21.00	32.78	46.40	72.3	108.4	252	[1, 18]
$h_{\ell}, \text{kJ/kg}$	0.0	60.1	121.8	190.2	257.6	331.8	400.1	484.0			[84]
$h_g, \text{kJ/kg}$	677.8	688.0	736.8	767.9	796.1	822.9	841.7	851.5			[104]
$\Delta h_{g,\ell}, \text{kJ/kg}$	677.8	627.9	615.0	577.7	538.5	491.1	441.6	367.5	284.5	82.5	[1, 19]
$c_{p,\ell}, \text{kJ/(kg K)}$	3.37	3.55	3.71	3.88	4.04	4.20	4.34	4.49			[18]
$c_{p,g}, \text{kJ/(kg K)}$	1.63	1.71	1.80	1.94	2.15	2.37	2.83	3.97			[14, 20, 106]
$\eta_{\ell}, \mu\text{Ns/m}^2$	502	376	295	230	184	147	122	93.5	72.5		[1]
$\eta_g, \mu\text{Ns/m}^2$	9.08	9.80	10.3	10.9	11.4	11.9	12.5	13.7	15.2	28.2	[1, 21]
$\lambda_{\ell}, (\text{mW/m}^2)/(\text{K/m})$	131.1	127.5	124.3	122.8	120.1	117.3	115.8	113.2	110.7	107.7	[1]
$\lambda_g, (\text{mW/m}^2)/(\text{K/m})$	19.8	22.2	24.6	27.1	29.3	31.8	34.9	38.9	42.3	47.1	[1, 22, 107]
Pr_{ℓ}	12.9	10.5	8.81	1.27	6.19	5.27	4.57	3.71			[12]
Pr_g	0.75	0.75	0.75	0.78	0.84	0.89	1.01	1.40			[12]
$\sigma, \text{mN/m}$	18.6	17.2	14.2	11.84	9.4	6.9	4.97	2.6	1.05	0.000	[1, 27]
$\beta_{e,\ell}, \text{K}^{-1}$	1.41	1.81	2.27	2.65	3.20	3.95	5.10	7.76	37.3		[10]

n-BUTANOLChemical formula: $\text{C}_4\text{H}_9\text{OH}$

Molecular weight: 74.12

Normal boiling point: 390.65 K

Melting point: 183.2 K

Critical temperature: 561.15 K

Critical pressure: 4 960 kPa

Critical density: 270.5 kg/m³

T_{sat}, K	390.65	410.2	429.2	446.5	469.5	485.2	508.3	530.2	545.5	558.9	
$p_{\text{sat}}, \text{kPa}$	101.3	182	327	482	759	1 190	1 830	2 530	3 210	4 030	[18]
$\rho_{\ell}, \text{kg/m}^3$	712	688	664	640	606	581	538	487	440	364	[6]
$\rho_g, \text{kg/m}^3$	2.30	4.10	7.9	12.5	23.8	27.8	48.2	14.0	102.3	240.2	[18]
$h_{\ell}, \text{kJ/kg}$	0.0	64.8	135.0	206.8	315.3	399.6	541.9	700.2			[84]
$h_g, \text{kJ/kg}$	591.3	629.8	672.3	716.5	784.1	836.8	924.4	1015.3			[104]
$\Delta h_{g,\ell}, \text{kJ/kg}$	591.3	565.0	537.3	509.7	468.8	437.2	382.5	315.1	248.4	143.0	[19]
$c_{p,\ell}, \text{kJ/(kg K)}$	3.20	3.54	3.95	4.42	5.15	5.74	6.71	7.76			[6]
$c_{p,g}, \text{kJ/(kg K)}$	1.87	1.95	2.03	2.14	2.24	2.37	2.69	3.05	3.97		[5, 20, 106]
$\eta_{\ell}, \mu\text{Ns/m}^2$	403.8	346.1	278.8	230.8	188.5	144.2	130.8	115.4	111.5	105.8	[7]
$\eta_g, \mu\text{Ns/m}^2$	9.29	10.3	10.7	11.4	12.1	12.7	13.9	15.4	17.1	28.3	[7, 21]
$\lambda_{\ell}, (\text{mW/m}^2)/(\text{K/m})$	127.1	122.3	117.5	112.6	105.4	101.4	91.7	82.9	74.0	62.8	[6]
$\lambda_g, (\text{mW/m}^2)/(\text{K/m})$	21.7	24.2	26.7	28.2	31.3	33.1	36.9	40.2	43.6	51.5	[7, 22, 107]
Pr_{ℓ}	10.3	9.86	9.17	8.64	10.2	8.10	8.67	9.08			[12]
Pr_g	0.81	0.83	0.81	0.86	0.87	0.91	1.01	1.17	1.56		[12]
$\sigma, \text{mN/m}$	17.1	15.6	13.9	12.3	10.2	7.50	6.44	4.23	2.11	0.96	[6]
$\beta_{e,\ell}, \text{K}^{-1}$	1.69	1.92	2.19	2.46	2.98	3.48	4.90	8.45	14.7		[10]

***t*-BUTYL ALCOHOL**Chemical formula: $(\text{CH}_3)_3\text{COH}$

Molecular weight: 74.12

Normal boiling point: 355.6 K

Melting point: 298.8 K

Critical temperature: 506.2 K

Critical pressure: 3 970 kPa

Critical density: 270 kg/m³

T_{sat} , K	355.6	375	390	405	420	435	450	465	480	506.2	
p_{sat} , kPa	101.3	207	322	483	779	1 010	1 516	1896	2 619	3 970	[46]
ρ_{L} , kg/m ³	710	688	670	647	621	596	567	533	487	270	[46]
ρ_{g} , kg/m ³	2.64	5.12	8.11	12.4	18.5	27.1	39.1	56.4	82.3	270	[62, 106]
h_{L} , kJ/kg	-182.0	-130.7	-78.4	-35.2	15.0	63.3	117.4	171.2	238.1	351.6	[67]
h_{g} , kJ/kg	324.6	355.0	378.0	400.2	421.1	440.1	456.5	468.5	472.6	351.6	[62, 63, 69, 106]
$\Delta h_{\text{g,L}}$, kJ/kg	506.6	485.7	456.4	435.4	406.1	376.8	339.1	297.3	234.5		[46]
$c_{p,\text{L}}$, kJ/(kg K)	2.90	3.06	3.19	3.34	3.47	3.62	3.79	4.01	4.38		[70]
$c_{p,\text{g}}$, kJ/(kg K)	1.81	1.92	2.02	2.13	2.26	2.42	2.64	3.00	3.73		[46, 62, 106]
η_{L} , $\mu\text{Ns/m}^2$	531	312	235	180	142	118	98	84	66	65	[71, 331]
η_{g} , $\mu\text{Ns/m}^2$	9.4	10.0	10.4	11.0	11.5	12.1	12.8	13.6	14.8	65	[46, 211]
λ_{L} , (mW/m ²)/(K/m)	109	104	100	96	92	88	83	77	70	53	[46, 34]
λ_{g} , (mW/m ²)/(K/m)	17.9	19.8	21.4	23.1	24.9	26.9	29.1	31.6	34.5	53	[46, 22, 107]
Pr_{L}	14.1	9.18	7.50	6.26	5.36	4.85	4.47	4.37	4.13		[12]
Pr_{g}	0.95	0.97	0.98	1.01	1.04	1.09	1.16	1.29	1.59		[12]
σ , mN/m	14.5	13.0	11.5	10.0	8.6	7.1	5.5	3.8	2.2		[46, 65]
$\beta_{e,\text{L}}$, K^{-1}	1.84	2.09	2.32	3.21	3.47	3.85	4.57	5.98	9.13		[10]

PHENOLChemical formula: $\text{C}_6\text{H}_5\text{OH}$

Molecular weight: 94.1

Normal boiling point: 454.95 K

Melting point: 313.90 K

Critical temperature: 693.2 K

Critical pressure : 6 130 kPa

Critical density: 435.7 kg/m³

T_{sat} , K	455 101.3	480 216	494 305	503 330	515 1 100	530 1650	545 2 360	565 3410	595 665 720	635 693.15 129	[75]
p_{sat} , kPa											
ρ_{L} , kg/m ³	955	932	905	877	851	809	772	713	636	436	[86]
ρ_{g} , kg/m ³	2.60	5.36	9.88	16.9	27.2	41.9	62.9	101	170	436	[62, 106]
h_{L} , kJ/kg	-153	-93	-41	20	80	147	206	290	399	514	[67]
h_{g} , kJ/kg	336	374	411	447	482	515	545	575	587	514	[82, 62, 69, 106]
$\Delta h_{\text{g,L}}$, kJ/kg	489	467	452	427	402	368	339	285	188		[66]
$c_{p,\text{L}}$, kJ/(kg K)	2.55	2.61	2.66	2.76	2.85	3.01	3.10	3.43	3.77		[5]
$c_{p,\text{g}}$, kJ/(kg K)	1.63	1.74	1.85	1.95	2.06	2.22	2.44	2.94	5.10		[30, 62, 106]
η_{L} , $\mu\text{Ns/m}^2$	351	256	219	166	137	113	90.1	75.2	65.3	45.3	[25]
η_{g} , $\mu\text{Ns/m}^2$	12.8	13.5	14.3	15.2	16.2	17.3	18.6	20.2	23.4	45.3	[26, 211]
λ_{L} , (mW/m ²)/(K/m)	175	170	166	162	157	154	149	141	130	92	[7]
λ_{g} , (mW/m ²)/(K/m)	28.9	31.6	34.8	38.4	42.4	46.8	51.4	56.2	64.3	92	[31, 22, 107]
Pr_{L}	5.11	3.93	3.51	2.83	2.59	2.21	1.87	1.57	1.89		[12]
Pr_{g}	0.72	0.74	0.76	0.77	0.79	0.82	0.88	1.07	1.86		[12]
σ , mN/m	24.5	20.9	18.2	14.6	12.4	10.2	7.6	5.3	2.7		[6]
$\beta_{e,\text{L}}$, K^{-1}	0.91	1.05	1.27	1.34	1.83	2.41	3.25	4.72	15.6		[10]

REFRIGERANT 12

Chemical formula: CCl_2F
 Molecular weight: 120.92
 Normal boiling point: 243.2 K
 Melting point: 118 K

Critical temperature: 384.8 K
 Critical pressure: 4 132 kPa
 Critical density: 561.8 kg/m³

T_{sat} , K	243.2	260	275	290	305	320	335	350	365	384.8	
p_{sat} , kPa	101.3	200	333	528	793	1 145	1602	2 183	2 907	4 132	[1]
ρ_{ℓ} , kg/m ³	1486	1436	1 388	1 338	1 284	1 225	1 157	1075	969.7	561.8	[1]
ρ_g , kg/m ³	6.33	11.8	19.2	29.9	44.8	65.4	94.6	136.4	203.2	561.8	[1]
h_{ℓ} , kJ/kg	473.6	488.3	501.9	516.3	531.1	546.8	563.8	582.3	603.2	649.8	[1]
h_g , kJ/kg	641.9	649.8	656.6	662.9	668.8	674.0	677.8	679.9	679.0	649.8	[1]
$\Delta h_{g,\ell}$, kJ/kg	168.3	161.5	154.7	146.6	137.7	127.2	114.0	97.6	75.8		[1]
$c_{p,\ell}$, kJ/(kg K)	0.896	0.911	0.932	0.957	0.990	1.03	1.08	1.13	1.22		[3]
$c_{p,g}$, kJ/(kg K)	0.569	0.614	0.646	0.689	0.746	0.825	0.920	1.22	1.68		[3, 20]
η_{ℓ} , $\mu\text{Ns/m}^2$	373	303	262	231	208	187	167	144	119		[4]
η_g , $\mu\text{Ns/m}^2$	10.3	11.0	11.7	12.5	13.3	14.2	15.2	16.5	18.1		[4]
λ_{ℓ} , (mW/m ²)/(K/m)	95.1	87.4	80.5	73.3	66.8	59.8	53.0	46.2	39.2	15.4	[2]
λ_g , (mW/m ²)/(K/m)	6.9	7.7	8.4	9.2	10.0	10.8	11.6	12.3	13.4	15.4	[2, 22]
Pr_{ℓ}	3.51	3.16	3.03	3.02	3.14	3.22	3.40	3.52	3.70		[12]
Pr_g	0.85	0.88	0.90	0.94	0.99	1.08	1.21	1.64	2.27		[12]
σ , mN/m	15.5	13.5	11.4	9.4	7.1	5.9	4.2	2.8	1.3		[23]
$\beta_{e,\ell}$, K^{-1}	1.96	2.22	1.50	2.87	3.36	4.17	5.48	8.50	14.5		[10]

REFRIGERANT 13

Chemical formula: CClF_3
 Molecular weight: 104.47
 Normal boiling point: 191.7 K
 Melting point: 93.2 K

Critical temperature: 302.28 K
 Critical pressure: 3 900 kPa
 Critical density: 5 71 kg/m³

T_{sat} , K	191.7	200	210	220	235	250	265	280	295	302.28	
p_{sat} , kPa	101.3	155	245	371	641	1060	1590	2 340	3 320	3 900	[1]
ρ_{ℓ} , kg/m ³	1521	1489	1450	1408	1339	1 257	1 175	1066	893	571	[1]
ρ_g , kg/m ³	6.89	10.3	15.8	23.4	39.9	67.2	103	166	290	571	[1]
h_{ℓ} , kJ/kg	417.1	424.6	433.9	443.3	458.1	474.5	489.8	509.1	532.8	562.0	[1]
h_g , kJ/kg	566.4	569.8	573.7	577.5	582.6	587.2	589.8	590.3	583.9	562.0	[1]
$\Delta h_{g,\ell}$, kJ/kg	149.3	145.2	139.8	134.2	124.5	112.7	100.0	81.2	51.1		[1]
$c_{p,\ell}$, kJ/(kg K)	1.11	1.13	1.16	1.21	1.27	1.36	1.56	1.96	3.92		[3, 42]
$c_{p,g}$, kJ/(kg K)	.529	.552	.588	.633	.696	.854	.962	1.30	2.52		[3, 20]
η_{ℓ} , $\mu\text{Ns/m}^2$	318	282	248	220	188	163	142	114	69.5		[4]
η_g , $\mu\text{Ns/m}^2$	9.83	10.3	10.8	11.3	12.2	13.2	14.3	15.8	19.9		[4]
λ_{ℓ} , (mW/m ²)/(K/m)	99.3	95.0	89.8	84.6	77.0	69.2	60.7	48.6	34.0	23.6	[1]
λ_g , (mW/m ²)/(K/m)	6.4	7.0	7.6	8.3	9.0	10.0	11.5	13.2	16.2	23.6	[2, 40, 22]
Pr_{ℓ}	3.55	3.35	3.20	3.15	3.10	3.20	3.65	4.56	8.01		[12]
Pr_g	0.81	0.82	0.84	0.86	0.94	1.13	1.20	1.56	3.10		[12]
σ , mN/m	13.5	12.3	10.8	9.41	7.36	5.41	3.58	1.91	0.49		[23]
$\beta_{e,\ell}$, K^{-1}	2.51	2.66	2.92	3.30	4.20	5.55	7.50	12.3	76.0		[10]

REFRIGERANT 2 1

Chemical formula: **CHCl₂F**
Molecular weight: 102.92
Normal boiling point: 28.19 K
Melting point: 138 K

Critical temperature: 451.25 K
Critical pressure: 181 kPa
Critical density: 525.0 kg/m³

T_{sat} , K	281.9	101.3	300.196	320.364	626.340	360.1010	380.1540	400.2240	420.3160	440.4350	451.25181	[1]
p_{sat} , kPa												
ρ_{L} , kg/m ³	1406	1360	1311	1258	1199	1134	1057	962.8	823.0	525		[1]
ρ_{G} , kg/m ³	4.62	8.55	15.48	26.14	41.93	64.94	98.91	151.1	124.1	525		[1]
h_{L} , kJ/kg	509.1	528.1	549.9	572.3	595.2	618.4	642.4	668.6	701.4	748.7		[1]
h_{G} , kJ/kg	748.1	756.5	765.5	773.6	780.5	786.6	790.7	791.5	785.3	748.7		[1]
$\Delta h_{\text{g,L}}$, kJ/kg	239.0	228.4	215.6	201.3	185.3	168.2	148.3	122.9	83.9			[1]
$c_{p,\text{L}}$, kJ/(kg K)	1.04	1.05	1.07	1.10	1.17	1.26	1.37	1.52	1.89			[3, 24]
$c_{p,\text{G}}$, kJ/(kg K)	0.721	.733	.780	.832	.902	.982	1.05	1.43	2.50			[3, 20]
η_{L} , $\mu\text{Ns/m}^2$	366	311	269	235	209	187	165	135	99			[4]
η_{G} , $\mu\text{Ns/m}^2$	11.0	11.7	12.5	13.3	14.3	15.4	16.5	18.3	25.0			[4]
λ_{L} , (mW/m ²)/(K/m)	11.4	108	101	94.2	87.5	80.7	73.8	66.7	59.9			[2]
λ_{G} , (mW/m ²)/(K/m)	7.9	8.6	9.5	10.4	11.4	12.5	13.7	15.2	16.7			[2, 22, 107]
Pr_{L}	3.34	3.02	2.85	2.74	2.79	2.89	3.06	3.08	3.12			[12]
Pr_{G}	1.00	1.01	1.03	1.06	1.13	1.21	1.26	1.72	3.74			[12]
σ , mN/m	20.1	17.6	14.7	12.1	9.4	7.0	4.7	2.6	0.73			[23]
$\beta_{e,\text{L}}$, K^{-1}	1.64	1.85	2.11	2.47	2.95	3.78	5.32	8.50	54.0			[10]

REFRIGERANT 22

Chemical formula: **CHClF**,
Molecular weight: 86.48
Normal boiling point : 242.4 K
Melting point: 113.2 K

Critical temperature: 369.3 K
Critical pressure: 986 kPa
Critical density: 513 kg/m³

T_{sat} , K	242.4	250	265	280	295	310	325	340	355	369.3	
p_{sat} , kPa	101.3	218	376	619	958	1420	2020	2800	3800	4986	[1]
ρ_{L} , kg/m ³	1413	1360	1313	1260	1206	1146	1076	991	877	513	[1]
ρ_{G} , kg/m ³	4.70	9.59	16.1	26.3	40.6	60.9	90.2	134	208	513	[1]
h_{L} , kJ/kg	453.6	469.3	490.2	508.1	526.3	545.2	565.3	587.3	613.2	667.3	[1]
h_{G} , kJ/kg	687.0	694.9	701.0	706.7	711.5	715.0	716.9	716.0	708.9	667.3	[1]
$\Delta h_{\text{g,L}}$, kJ/kg	233.4	225.6	210.8	198.6	185.2	169.8	151.6	128.7	95.7		[1]
$c_{p,\text{L}}$, kJ/(kg K)	1.10	1.13	1.16	1.19	1.24	1.30	1.41	1.65	2.43		[1, 39]
$c_{p,\text{G}}$, kJ/(kg K)	.599	.646	.691	.747	.820	.930	1.09	1.40	2.31		[3, 20]
η_{L} , $\mu\text{Ns/m}^2$	332	282	251	225	204	187	172	150	119		[4]
η_{G} , $\mu\text{Ns/m}^2$	10.1	10.9	11.7	12.3	13.2	14.2	15.7	16.4	18.8		[4]
λ_{L} , (mW/m ²)/(K/m)	11.9	109	101	94.2	86.6	78.8	70.2	59.2	44.0	31.9	[1]
λ_{G} , (mW/m ²)/(K/m)	7.15	8.22	9.10	10.1	11.2	12.4	14.0	16.0	18.8	31.9	[2, 22, 107]
Pr_{L}	3.07	2.92	2.88	2.84	2.92	3.09	3.45	4.18	6.89		[12]
Pr_{G}	.85	.86	.89	.91	.97	1.07	1.22	1.69	2.31		[12]
σ , mN/m	18.3	15.5	13.0	10.6	8.4	6.2	4.3	2.5	1.0		[1]
$\beta_{e,\text{L}}$, K^{-1}	2.08	2.37	2.68	3.10	3.67	4.65	6.34	9.56	25.6		[10]

ETHYL ETHER

Chemical formula: $(\text{CH}_3\text{CH}_2)_2\text{O}$

Molecular weight: 74.10

Normal boiling point: 307.8 K

Melting point: 158.9 K

Critical temperature: 467 K

Critical pressure: 3 610 kPa

Critical density: 265 kg/m³

T_{sat}, K	307.75	323	343	363	383	403	423	443	458	463	
$p_{\text{sat}}, \text{kPa}$	101.3	170	307	511	811	1220	1 770	2490	3 150	3490	[1]
$\rho_{\text{L}}, \text{kg/m}^3$	696.2	676.4	653.2	625.0	594.2	558.0	517.9	465.8	401.8	366.3	[1]
$\rho_{\text{g}}, \text{kg/m}^3$	3.16	5.08	8.92	14.77	23.49	36.38	55.51	87.31	132.0	162.0	[1]
$h_{\text{L}}, \text{kJ/kg}$	0.0	36.6	85.9	137.0	190.3	248.6	305.0	367.1	416.1	433.0	[84]
$h_{\text{g}}, \text{kJ/kg}$	349.9	373.6	404.1	434.3	464.5	497.7	520.6	532.5	523.9	524.6	[104]
$\Delta h_{\text{g,L}}, \text{kJ/kg}$	349.9	337.0	318.2	297.3	274.2	249.1	215.6	165.4	107.8	81.6	[1]
$c_{p,\text{L}}, \text{kJ/(kg K)}$	2.37	2.43	2.51	2.61	2.12	2.86	3.01	3.20	3.75	4.07	[1]
$c_{p,\text{g}}, \text{kJ/(kg K)}$	1.40	1.96	2.05	2.14	2.26	2.43	2.75	3.44	4.15	4.50	[30, 20]
$\eta_{\text{L}}, \mu\text{Ns/m}^2$	210	177	148	127	109	95	84	17	70	67	[1, 17]
$\eta_{\text{g}}, \mu\text{Ns/m}^2$	7.86	8.28	8.86	9.45	10.1	10.9	11.7	13.1	15.0	16.4	[4, 21,
$\lambda_{\text{L}}, (\text{mW/m}^2)/(\text{K/m})$	126	120	112	104	95.6	87.5	79.9	71.4	65.3	63.3	[2]
$\lambda_{\text{g}}, (\text{mW/m}^2)/(\text{K/m})$	15.8	17.4	19.5	22.4	24.2	27.0	30.2	34.2	38.6	41.5	[2, 22]
Pr_{L}	3.95	3.58	3.32	3.19	3.10	3.11	3.16	3.45	4.02	4.31	[12]
Pr_{g}	0.70	0.93	0.93	0.90	0.94	0.98	1.07	1.32	1.61	1.78	[12]
$\sigma, \text{mN/m}$	15.25	13.5	11.3	9.1	7.0	4.9	3.1	1.5	0.5	0.2	[1]
$\beta_{e,\text{L}}, \text{K}^{-1}$	1.93	1.80	2.00	2.48	3.27	4.38	6.10	8.82	25.8	45.7	[10]

METHYL-*t*-BUTYL ETHERChemical formula: $\text{CH}_3, \text{OC}, \text{H}_9$

Molecular weight: 88.1

Normal boiling point: 33 1.2 K

Melting point: 162.4 K

Critical temperature: 503.4 K

Critical pressure: 3 411 kPa

Critical density: 275 kg/m³

T_{sat}, K	331.2	340	360	380	400	420	440	460	480	503.4	
$p_{\text{sat}}, \text{kPa}$	101.3	133	234	386	602	897	1 290	1800	2440	3411	[75]
$\rho_{\text{L}}, \text{kg/m}^3$	706	697	673	649	623	591	556	517	467	27.5	[77]
$\rho_{\text{g}}, \text{kg/m}^3$	3.40	4.39	7.51	12.2	18.9	28.5	42.3	62.7	96.2	275	[62]
$h_{\text{L}}, \text{kJ/kg}$	-22.2	-1.7	46.5	96.6	148.7	203.1	259.8	319.2	382	488.1	[67]
$h_{\text{g}}, \text{kJ/kg}$	292.2	306.6	339.8	373.7	407.8	441.8	474.9	505.4	529.3	488.1	[78, 69, 62]
$\Delta h_{\text{g,L}}, \text{kJ/kg}$	314.4	308.3	293.3	277.1	259.1	238.7	215.1	186.3	147.3		[79, 19]
$c_{p,\text{L}}, \text{kJ/(kg K)}$	2.30	2.35	2.46	2.57	2.69	2.83	3.01	3.27	3.83		[80]
$c_{p,\text{g}}, \text{kJ/(kg K)}$	1.78	1.83	1.95	2.08	2.23	2.39	2.61	2.95	3.76		[78, 62]
$\eta_{\text{L}}, \mu\text{Ns/m}^2$	231	214	184	151	129	109	9 1	74	59	44	[71, 73]
$\eta_{\text{g}}, \mu\text{Ns/m}^2$	8.50	8.76	9.38	10.0	10.7	11.5	12.3	13.3	14.9	44	[81, 21]
$\lambda_{\text{L}}, (\text{mW/m}^2)/(\text{K/m})$	108	106	100	94	89	83	78	71	62	47	[34]
$\lambda_{\text{g}}, (\text{mW/m}^2)/(\text{K/m})$	15.4	16.2	18.2	20.3	22.5	24.9	27.6	30.7	34.4	47	[58, 22]
Pr_{L}	4.90	4.76	4.53	4.12	3.92	3.73	3.52	3.36	3.53		[12]
Pr_{g}	0.98	0.99	1.01	1.02	1.06	1.10	1.16	1.28	1.63		[12]
$(\text{l}, \text{mN/m})$	14.7	13.8	11.7	9.8	7.9	6.1	4.3	2.7	1.3		[65]
$\beta_{e,\text{L}}, \text{K}^{-1}$	1.56	1.64	1.85	2.13	2.46	3.05	4.09	5.62	10.1		1771

ETHYLENE OXIDE

Chemical formula: $(\text{CH}_2)_2\text{O}$
Molecular weight: 44.054
Normal boiling point: 283.5 K
Melting point: 161 K

Critical temperature: 469 K
Critical pressure: 7 194 kPa
Critical density: 315 kg/m³

T_{sat}, K	283.5	300	320	340	360	380	400	420	440	469	
$p_{\text{sat}}, \text{kPa}$	101.3	186	359	621	1030	1660	2480	3450	4830	7 194	[47]
$\rho_{\text{L}}, \text{kg/m}^3$	889	866	835	804	760	721	691	682	584	315	[90]
$\rho_{\text{G}}, \text{kg/m}^3$	1.94	3.44	6.33	10.8	17.5	27.2	41.1	61.6	93.9	315	[62]
$h_{\text{L}}, \text{kJ/kg}$	-440	-409	-367	-333	-289	-238	-183	-129	-65	66	[67]
$h_{\text{G}}, \text{kJ/kg}$	129	144	161	178	193	206	215	219	211	66	[30, 62, 69]
$\Delta h_{\text{G,L}}, \text{kJ/kg}$	569	553	528	511	482	444	398	348	276		[47]
$c_{p,\text{L}}, \text{kJ/(kg K)}$	1.96	2.01	2.09	2.19	2.32	2.48	2.68	2.92	3.21		[5]
$c_{p,\text{G}}, \text{kJ/(kg K)}$	1.09	1.17	1.28	1.40	1.55	1.73	1.99	2.47	3.40		[30, 62]
$\eta_{\text{L}}, \mu\text{Ns/m}^2$	284	245	210	182	160	142	128	116	105	47	[25, 47]
$\eta_{\text{G}}, \mu\text{Ns/m}^2$	9.0	9.6	10.3	11.0	11.7	12.5	13.4	14.4	15.9	47	[27, 47, 21]
$\lambda_{\text{L}}, (\text{mW/m}^2)/(\text{K/m})$	158	152	144	135	127	119	110	102	93	69	[7, 47]
$\lambda_{\text{G}}, (\text{mW/m}^2)/(\text{K/m})$	11.5	13.6	16.3	19.3	22.5	25.1	29.9	34.5	40.4	69	[31, 47]
Pr_{L}	3.52	3.24	3.04	2.93	2.92	2.97	3.12	3.34	3.63		[12]
Pr_{G}	0.85	0.83	0.81	0.80	0.81	0.86	0.89	1.01	1.34		[12]
$\sigma, \text{mN/m}$	25.87	23.24	20.10	17.03	14.03	11.11	8.29	5.59	3.05		[82]
$\beta_{\text{e,L}}, \text{kK}^{-1}$	1.60	1.76	1.98	2.30	2.71	3.30	4.20	5.76	9.26		[10]

PROPYLENE OXIDE

Chemical formula: $\text{CH}_2(\text{CHCH}_2)\text{O}$
Molecular weight: 58.08
Normal boiling point: 307.5 K
Melting point: 161 K

Critical temperature: 482.2 K
Critical pressure: 4 920 kPa
Critical density: 312 kg/m³

T_{sat}, K	307.5	320	340	360	380	400	420	440	460	482.2	
$p_{\text{sat}}, \text{kPa}$	101.3	159	297	496	814	1 230	1 790	2480	3450	4920	[47]
$\rho_{\text{L}}, \text{kg/m}^3$	812	796	769	740	709	675	636	491	531	312	[90]
$\rho_{\text{G}}, \text{kg/m}^3$	2.38	3.57	6.39	10.7	17.2	26.6	40.5	61.1	95.9	312	[62]
$h_{\text{L}}, \text{kJ/kg}$	-293	-271	-220	-177	-135	-86	-37	33	106	200	[67]
$h_{\text{G}}, \text{kJ/kg}$	184	198	220	242	263	282	298	309	307	200	[30, 62, 69]
$\Delta h_{\text{G,L}}, \text{kJ/kg}$	477	469	440	419	398	368	335	276	201		[47]
$c_{p,\text{L}}, \text{kJ/(kg K)}$	2.06	2.10	2.18	2.29	2.42	2.60	2.81	3.07	3.38		[5]
$c_{p,\text{G}}, \text{kJ/(kg K)}$	1.32	1.39	1.49	1.62	1.76	1.94	2.19	2.63	3.83		[30, 62]
$\eta_{\text{L}}, \mu\text{Ns/m}^2$	278	251	217	191	171	155	143	133	125	48	[25]
$\eta_{\text{G}}, \mu\text{Ns/m}^2$	9.1	9.5	10.2	10.8	11.5	12.3	13.1	14.1	15.5	48	[26, 47, 21]
$\lambda_{\text{L}}, (\text{mW/m}^2)/(\text{K/m})$	147	143	135	128	120	113	105	96	88	71	17,471
$\lambda_{\text{G}}, (\text{mW/m}^2)/(\text{K/m})$	12.1	13.3	15.5	17.8	20.5	23.5	26.9	31.3	47.4	71	[31, 47]
Pr_{L}	3.90	3.69	3.49	3.41	3.44	3.57	3.84	4.23	4.79		[12]
Pr_{G}	0.99	0.99	0.98	0.98	0.99	1.02	1.07	1.18	1.25		[12]
$\sigma, \text{mN/m}$	19.9	18.2	15.5	12.9	10.4	8.0	5.7	3.5	1.6		[82]
$\beta_{\text{e,L}}, \text{kK}^{-1}$	1.59	1.71	1.9	2.24	2.64	3.27	4.26	6.22	19.4		[10]

METHYL ACETATEChemical formula: CH₃CO, CH₃

Molecular weight: 74.08

Normal boiling point: 330.3 K

Melting point: 174.45 K

Critical temperature: 506.8 K

Critical pressure: 4 687 kPa

Critical density: 325 kg/m³

T_{sat}, K	331	350	370	390	410	430	450	470	490	506.8	
$p_{\text{sat}}, \text{kPa}$	101.3	200	359	537	854	1 344	1930	2 688	3 723	4 687	[47]
$\rho_{\text{L}}, \text{kg/m}^3$	875	850	820	780	750	715	680	620	540	325	[47]
$\rho_{\text{G}}, \text{kg/m}^3$	2.83	5.16	8.87	14.5	22.7	34.6	52.2	79.3	127.8	325	[62]
$h_{\text{L}}, \text{kJ/kg}$	-173.4	-136.1	-96.5	-57.7	-17.8	26.7	76.4	126.7	196.4	254.6	[67]
$h_{\text{G}}, \text{kJ/kg}$	228.5	249.1	269.8	289.8	308.8	326.0	340.2	348.6	342.9	254.6	[63, 62]
$\Delta h_{\text{G,L}}, \text{kJ/kg}$	401.9	385.2	366.3	347.5	326.6	297.3	263.8	221.9	146.5		[47]
$c_{p,\text{L}}, \text{kJ/(kg K)}$	1.92	1.99	2.08	2.18	2.32	2.46	2.65	2.94	3.58		[70]
$c_{p,\text{G}}, \text{kJ/(kg K)}$	1.19	1.25	1.35	1.45	1.57	1.72	1.95	2.38	3.86		147,621
$\eta_{\text{L}}, \mu\text{Ns/m}^2$	260	225	192	168	145	121	99	80	62	56	147,711
$\eta_{\text{G}}, \mu\text{Ns/m}^2$	8.9	9.5	10.1	10.7	11.4	12.1	13.1	14.1	16.1	56	[47, 21]
$\lambda_{\text{L}}, (\text{mW/m}^2)/(\text{K/m})$	157	146	133	122	110	98	86	74	61	50.3	[47, 22]
$\lambda_{\text{G}}, (\text{mW/m}^2)/(\text{K/m})$	14.2	15.7	17.5	19.5	21.7	24.1	27.0	30.4	35.3	50.3	147,221
Pr_{L}	3.18	3.07	3.00	3.00	3.04	3.05	3.06	3.18	3.64		[12]
Pr_{G}	0.75	0.76	0.78	0.80	0.82	0.86	0.95	1.10	1.76		[12]
$\sigma, \text{mN/m}$	19.4	17.0	14.7	12.0	9.4	6.9	4.6	2.4	1.1		[47, 65]
$\beta_{\text{e,L}}, \text{K}^{-1}$	1.64	1.84	2.11	2.46	2.95	3.67	4.86	7.22	14.4		[10]

ETHYL ACETATEChemical formula: CH₃CO, C₂H₅

Molecular weight: 88.10

Normal boiling point: 350.25 K

Melting point: 189.55 K

Critical temperature: 523.25 K

Critical pressure: 3 832 kPa

Critical density: 307.7 kg/m³

T_{sat}, K	350.25	370	390	410	430	450	470	490	510	523.25	
$p_{\text{sat}}, \text{kPa}$	101.3	193	310	510	792	1 172	1 655	2 275	3 172	3 832	[47]
$\rho_{\text{L}}, \text{kg/m}^3$	830	800	770	740	705	670	625	570	475	307.7	1471
$\rho_{\text{G}}, \text{kg/m}^3$	3.20	5.63	9.45	15.1	23.4	35.5	54.2	81.3	134.5	307.7	[62]
$h_{\text{L}}, \text{kJ/kg}$	-89.7	-47.3	-6.7	35.7	81.3	131.7	182.0	241.7	315.8	362.8	[67]
$h_{\text{G}}, \text{kJ/kg}$	274.6	300.2	326.2	351.8	376.5	399.6	420.6	434.3	433.0	362.8	[63, 62, 691]
$\Delta h_{\text{G,L}}, \text{kJ/kg}$	364.3	347.5	332.9	316.1	295.2	267.9	238.6	192.6	117.2		[47]
$c_{p,\text{L}}, \text{kJ/(kg K)}$	2.10	2.17	2.28	2.36	2.50	2.64	2.82	3.09	3.76		147,701
$c_{p,\text{G}}, \text{kJ/(kg K)}$	1.46	1.54	1.63	1.73	1.85	2.00	2.25	2.68	4.52		[63, 62]
$\eta_{\text{L}}, \mu\text{Ns/m}^2$	255	221	193	158	134	111	90	72	56	57	171,331
$\eta_{\text{G}}, \mu\text{Ns/m}^2$	8.9	9.5	10.1	10.7	11.4	12.2	13.0	14.3	16.4	57	147,141
$\lambda_{\text{L}}, (\text{mW/m}^2)/(\text{K/m})$	125	118	111	104	98	92	85	77	66	48.2	[34, 22]
$\lambda_{\text{G}}, (\text{mW/m}^2)/(\text{K/m})$	15.8	17.4	19.3	21.5	23.5	25.8	28.5	32.0	36.5	48.2	(47,221
Pr_{L}	4.28	4.08	3.96	3.59	3.42	3.19	2.99	2.89	3.19		[12]
Pr_{G}	0.82	0.84	0.85	0.86	0.90	0.95	1.03	1.20	2.03		[12]
$\sigma, \text{mN/m}$	17.4	15.0	12.6	10.0	7.8	5.8	3.9	2.3	0.14		[12]
$\beta_{\text{e,L}}, \text{K}^{-1}$	1.65	1.86	2.14	2.50	3.02	3.79	5.17	7.80	17.4		[10]

CHLOROFORM

Chemical formula: CHCl_3
Molecular weight: 119.4
Normal boiling point: 334.5 K
Melting point: 209.9 K

Critical temperature: 536.4 K
Critical pressure: 470 kPa
Critical density: 498 kg/m³

T_{sat} , K	334.5	360	380	400	420	440	460	480	505	536.4	
p_{sat} , kPa	101.3	221	374	599	914	1321	1893	2598	3725	5470	[91]
ρ_{L} , kg/m ³	1415	1361	1333	1282	1248	1184	1114	1050	969	498	[90]
ρ_{g} , kg/m ³	4.50	9.33	15.3	23.4	36.1	53.0	77.3	109	158	498	[62]
h_{L} , kJ/kg	-108	-79	-61	-41	-17	4	27	45	67	136	[67]
h_{g} , kJ/kg	141	154	164	173	181	188	194	197	197	136	[62, 63, 691]
$\Delta h_{\text{g,L}}$, kJ/kg	249	233	225	214	198	184	167	152	130		[66]
$c_{p,\text{L}}$, kJ/(kg K)	1.00	1.03	1.07	1.11	1.15	1.21	1.32	1.43	1.59		[5]
$c_{p,\text{g}}$, kJ/(kg K)	0.60	0.63	0.66	0.69	0.73	0.79	0.87	1.00	1.28		[62, 63]
η_{L} , $\mu\text{Ns/m}^2$	400	342	299	267	220	197	181	165	150	65	1251
η_{g} , $\mu\text{Ns/m}^2$	11.2	12.2	13.0	13.7	14.6	15.5	16.5	17.9	19.8	65	[26, 21]
λ_{L} , (mW/m ²)/(K/m)	111	107	103	98.4	94.2	91.3	81.6	73.3	69.1	26.8	171
λ_{g} , (mW/m ²)/(K/m)	8.7	9.74	10.6	11.5	12.5	13.5	13.6	15.9	17.5	26.8	[31, 22]
Pr_{L}	3.60	3.29	3.11	3.01	2.69	2.61	2.93	3.22	3.45		[12]
Pr_{g}	0.17	0.79	0.81	0.81	0.85	0.91	1.06	1.13	1.45		[12]
σ , mN/m	22.5	18.6	16.0	13.6	11.2	9.5	6.8	5.9	3.1		[6]
$\beta_{\text{e,L}}$, K^{-1}	1.38	1.58	1.78	2.03	2.36	2.82	3.54	4.63	6.86		[10]

ANILINE

Chemical formula: $\text{C}_6\text{H}_5\text{NH}_2$
Molecular weight: 93.06
Normal boiling point: 457.55 K
Melting point: 267.05 K

Critical temperature: 699.0 K
Critical pressure: 5301 kPa
Critical density: 340 kg/m³

T_{sat} , K	457.5	500	525	550	575	600	625	650	675	699.0	
p_{sat} , kPa	101.3	276	456	716	1080	1560	2200	3010	4050	5300	[1]
ρ_{L} , kg/m ³	875	828	800	769	736	699	658	608	541	340	[47]
ρ_{g} , kg/m ³	2.56	6.62	10.7	16.7	25.3	37.5	55.1	81.7	128	340	[62]
h_{L} , kJ/kg	-114	-10	53	137	184	254	323	396	473	584	[67]
h_{g} , kJ/kg	357	427	468	509	549	589	623	653	669	584	[63, 62, 691]
$\Delta h_{\text{g,L}}$, kJ/kg	471	437	415	372	365	335	300	257	196		[47]
$c_{p,\text{L}}$, kJ/(kg K)	2.37	2.52	2.61	2.71	2.84	2.97	3.13	3.36	3.84		[70]
$c_{p,\text{g}}$, kJ/(kg K)	1.74	1.89	1.99	2.09	2.20	2.35	2.55	2.90	3.95		[63, 62]
η_{L} , $\mu\text{Ns/m}^2$	303	213	178	152	132	117	104	94	86	71	[25]
η_{g} , $\mu\text{Ns/m}^2$	11.8	13.1	13.9	14.7	15.6	16.5	17.6	19.0	21.1	71	[26, 21]
λ_{L} , (mW/m ²)/(K/m)	154	146	141	136	131	126	121	116	111	70	[7]
λ_{g} , (mW/m ²)/(K/m)	23.5	28.1	30.9	33.8	36.8	40.1	43.6	47.8	53.1	70	[31, 22]
Pr_{L}	4.66	3.68	3.29	3.03	2.86	2.76	2.69	2.72	2.98		[12]
Pr_{g}	0.87	0.88	0.89	0.91	0.93	0.97	1.03	1.15	1.57		[12]
σ , mN/m	25.2	19.9	16.9	14.0	11.2	8.5	5.9	3.6	1.5		[65]
$\beta_{\text{e,L}}$, K^{-1}	1.17	1.42	1.62	1.88	2.24	2.17	3.62	5.26	9.82		[10]

ACETIC ACID

Chemical formula: CH₃CO₂H
Molecular weight: 60.05
Normal boiling point: 391.15 K
Melting point: 289.85 K

Critical temperature: 594.75 K
Critical pressure: 5 790 kPa
Critical density: 350.6 kg/m³

T_{sat}, K	391.15	420	440	460	480	500	520	540	560	594.75	
$p_{\text{sat}}, \text{kPa}$	101.3	230	382	427	898	1 320	1 890	2630	3590	5790	[1]
$\rho_{\text{L}}, \text{kg/m}^3$	939	900	874	846	815	782	743	697	642	350.6	[1]
$\rho_{\text{g}}, \text{kg/m}^3$	1.93	4.53	7.56	12.0	18.4	27.3	39.9	57.8	85.0	350.6	[62, 106]
$h_{\text{L}}, \text{kJ/kg}$	260	326	372	420	413	524	480	643	710	854	1971
$h_{\text{g}}, \text{kJ/kg}$	642	703	740	775	807	834	850	874	882	854	[97]
$\Delta h_{\text{g,L}}, \text{kJ/kg}$	382	377	368	355	334	310	270	231	172		[85]
$c_{p,\text{L}}, \text{kJ/(kg K)}$	2.42	2.55	2.66	2.76	2.91	3.04	3.21	3.43	3.82		[70]
$c_{p,\text{g}}, \text{kJ/(kg K)}$	1.39	1.49	1.58	1.69	1.82	1.99	2.24	2.66	3.59		[63, 62, 106]
$\eta_{\text{L}}, \mu\text{Ns/m}^2$	372	276	232	194	166	138	115	95	76		[98, 33]
$\eta_{\text{g}}, \mu\text{Ns/m}^2$	10.4	11.4	11.9	12.4	13.0	13.7	14.4	15.3	16.5		[98, 21]
$\lambda_{\text{L}}, (\text{mW/m}^2)/(\text{K/m})$	158	150	143	137	131	125	118	112	105	9 3	[59, 58, 521]
$\lambda_{\text{g}}, (\text{mW/m}^2)/(\text{K/m})$	20.7	23.8	26.3	29.0	32.2	35.9	40.3	45.9	53.6	93	[58, 22, 107]
Pr_{L}	5.70	4.69	4.32	3.91	3.69	3.36	3.13	2.91	2.76		[12]
Pr_{g}	0.70	0.71	0.71	0.12	0.73	0.76	0.80	0.89	1.11		[12]
$\sigma, \text{mN/m}$	18.1	15.3	13.5	11.6	9.7	7.9	6.0	4.28	2.47		[1, 27]
$\beta_{e,\text{L}}, \text{K}^{-1}$	1.40	1.52	1.63	1.87	2.24	2.15	3.62	5.15	8.0		[10]

ACETONE

Chemical formula: CH₃COCH₃
Molecular weight: 58.1
Normal boiling point: 329.25 K
Melting point: 179.95 K

Critical temperature: 508.15 K
Critical pressure: 4 761 kPa
Critical density: 273 kg/m³

T_{sat}, K	329.25	340	360	380	400	420	440	460	480	508.15	
$p_{\text{sat}}, \text{kPa}$	101.3	152	274	452	731	1 082	1637	2279	3252	4761	[1]
$\rho_{\text{L}}, \text{kg/m}^3$	750	736	710	683	655	625	590	553	504	273	[102]
$\rho_{\text{g}}, \text{kg/m}^3$	2.23	3.11	5.49	9.13	14.5	22.3	33.6	50.3	77.2	273	[62]
$h_{\text{L}}, \text{kJ/kg}$	-258	-233	-180	-131	-74	-32	23	79	138	257	[67]
$h_{\text{g}}, \text{kJ/kg}$	248	261	285	308	330	350	367	379	380	257	[13, 62, 69]
$\Delta h_{\text{g,L}}, \text{kJ/kg}$	506	494	465	439	414	382	344	300	242		[103, 19]
$c_{p,\text{L}}, \text{kJ/(kg K)}$	2.28	2.32	2.42	2.53	2.65	2.83	3.03	3.29	3.76		[100]
$c_{p,\text{g}}, \text{kJ/(kg K)}$	1.41	1.46	1.55	1.66	1.79	1.95	2.18	2.54	3.38		[13, 62]
$\eta_{\text{L}}, \mu\text{Ns/m}^2$	235	213	188	165	141	119	9 9	80	64	49	[103, 13, 331]
$\eta_{\text{g}}, \mu\text{Ns/m}^2$	9.4	9.8	10.4	11.1	11.8	12.6	13.5	14.4	15.8	49	[38, 21]
$\lambda_{\text{L}}, (\text{mW/m}^2)/(\text{K/m})$	142	137	129	121	112	104	96	a7	77	58	[34, 86, 22]
$\lambda_{\text{g}}, (\text{mW/m}^2)/(\text{K/m})$	12.7	14.1	16.1	18.5	21.2	24.2	27.2	31.0	36.0	58	[86, 22]
Pr_{L}	3.77	3.61	3.53	3.49	3.34	3.24	3.12	3.03	3.13		[12]
Pr_{g}	1.04	1.01	1.00	1.00	1.00	1.02	1.08	1.18	1.48		[12]
$\sigma, \text{mN/m}$	18.4	17.0	14.5	12.1	9.6	7.1	4.6	3.1	1.6		[101, 27]
$\beta_{e,\text{L}}, \text{K}^{-1}$	1.65	1.81	1.92	2.18	2.50	3.04	3.82	5.13	9.22		[10]

DOWTHERM AChemical formula: $(C_6H_5)_2O$ (73.5%); $(C_6H_5)_2$ (26.5%)

Molecular weight: 166

Normal boiling point: 530.25 K

Melting point: 285.15 K

Critical temperature: 770.15 K

Critical pressure: 3 134 kPa

Critical density: 315.5 kg/m³

T_{sat}, K	530.25	555	580	605	630	655	680	700	730	770.15	
p_{sat}, kPa	101.3	170.4	270	411	600	848	1 170	1470	2040	3 134	[108]
$\rho_l, kg/m^3$	851.9	826	799	770	740	706	670	637	573	315.5	[108]
$\rho_g, kg/m^3$	3.96	6.47	10.0	15.2	22.0	31.8	45.1	60.1	100	315.5	[108]
$h_l, kJ/kg$	465	522	580	642	703	769	835	890	970		[108, 39]
$h_g, kJ/kg$	761	806	850	897	942	990	1035	1070	1110		[108, 39]
$\Delta h_{g,l}, kJ/kg$	296	284	270	255	239	221	200	180	140		[108, 39]
$c_{p,l}, kJ/(kg K)$	2.24	2.32	2.40	2.47	2.53	2.59	2.69	2.83	3.26		(108,391)
$c_{p,g}, kJ/(kg K)$	1.83	1.91	1.97	2.03	2.10	2.16	2.24	2.34	2.54		[108, 39]
$\eta_l, \mu Ns/m^2$	273	236	206	180	160	145	132	124	115		[108, 110]
$\eta_g, \mu Ns/m^2$	10.1	10.6	11.2	11.7	12.2	12.7	13.3	13.9	14.5		[108, 93, 110]
$\lambda_l, (mW/m^2)/(K/m)$	112	109	106	103	100	97	94	91	88		[108, 93]
$\lambda_g, (mW/m^2)/(K/m)$	20.4	22.6	24.8	27.2	29.8	32.6	35.6	38.8	42.0		(108,931)
Pr_l	5.46	5.02	4.66	4.32	4.05	3.87	3.78	3.86	4.26		[12]
Pr_g	0.91	0.90	0.89	0.87	0.86	0.84	0.84	0.84	0.88		[12, 93]
$\sigma, mN/m$											[83]
$\beta_{e,l}, K^{-1}$	1.20	1.33	1.50	1.70	2.02	2.41	2.93	3.73	6.85		[10]

DOWTHERM JChemical formula: $C_{10}H_{14}$

Molecular weight : 134

Normal boiling point: 454.26 K

Melting point: < 235.37 K

Critical temperature: 656.15 K

Critical pressure: 2 837 kPa

Critical density: 273.82 kg/m³

T_{sat}, K	454.26	480	500	520	540	560	580	600	620	656.15	
p_{sat}, kPa	101.3	187	279	351	536	804	1 070	1460	1870	2837	[109]
$\rho_l, kg/m^3$	729.3	705.3	683.5	660.9	636.6	609.5	580.8	545.4	505.3	273.8	[109]
$\rho_g, kg/m^3$	3.75	6.70	9.79	14.2	20.3	28.7	39.5	63.9	96.4	273.8	[109]
$h_l, kJ/kg$	330	394	444	497	552	609	665	721	779		[109, 110]
$h_g, kJ/kg$	635	684	721	760	799	838	876	910	931		[109, 110]
$\Delta h_{g,l}, kJ/kg$	305	290	277	263	247	229	211	189	158		[109, 110]
$c_{p,l}, kJ/(kg K)$	2.40	2.51	2.58	2.66	2.75	2.84	2.95	3.08	3.25		[109, 110]
$c_{p,g}, kJ/(kg K)$	1.91	2.00	2.06	2.12	2.17	2.24	2.29	2.34	2.39		[109, 100]
$\eta_l, \mu Ns/m^2$	172	149	133	121	109	101	93	85	78		[109, 100]
$\eta_g, \mu Ns/m^2$	8.60	9.05	9.40	9.75	10.10	10.45	10.80	11.15	11.40		[109, 93]
$\lambda_l, (mW/m^2)/(K/m)$	118.5	117.0	115.6	114.2	111.8	110.4	109.0	107.6	106.2		[109]
$\lambda_g, (mW/m^2)/(K/m)$											[83]
Pr_l	3.48	3.20	2.91	2.82	2.68	2.60	2.52	2.43	2.39		[12]
Pr_g											[83]
$\sigma, mN/m$											[83]
$\beta_{e,l}, K^{-1}$	1.20	1.46	1.64	1.73	2.20	2.76	3.54	4.69	7.52		[10]

AIR

Chemical formula: N_2 (78.1%); O, (20.9%); Ar (0.9%)
 Molecular weight: 28.96
 Normal boiling point: 78.9 K
 Melting point: ?

Critical temperature: 132.6 K
 Critical pressure: 3 769 kPa
 Critical density: 3 13 kg/m³

T_{sat} , K	78.9	85	90	95	100	110	115	120	125	132.6	
p_{sat} , kPa	101.3	192	304	457	662	1 260	1670	2160	2740		[52]
p_{con} , kPa	0.721	1.45	2.40	3.75	6.60	11.2	15.2	20.1	26.1	37.69	[52]
ρ_l , kg/m ³	876	847	822	796	768	705	669	627	569		[52]
ρ_g , kg/m ³	3.27	6.26	9.98	15.2	22.4	45.1	62.8	87.3	123	313	[52]
h_l , kJ/kg	-124.6	-113.1	-103.5	-93.5	-83.3	-61.9	-50.3	-37.5	-22.0		[52]
h_g , kJ/kg	76.9	81.6	84.8	87.4	89.3	90.1	88.4	84.8	78.2	31.4	[52]
$\Delta h_{g,l}$, kJ/kg	201.5	194.7	188.3	180.9	172.6	152.0	138.7	122.3	100.2		[52]
$c_{p,l}$, kJ/(kg K)	1.87	1.91	1.94	1.99	2.05	2.14	2.48	2.92	4.59		[1]
$c_{p,g}$, kJ/(kg K)	1.05	1.07	1.09	1.13	1.26	1.56	1.92	2.46	3.38		[1]
η_l , μ Ns/m ²	183	142	116	97	82	63	55	48	41		[1]
η_g , μ Ns/m ²	5.6	6.0	6.4	6.8	7.3	8.5	9.0	9.8	10.9		[1]
λ_l , (mW/m ²)/(K/m)	148	137	128	120	111	94	85	77	66		[1]
λ_g , (mW/m ²)/(K/m)	7.4	7.8	8.4	9.2	10.1	12.5	13.9	15.2	17.4		[1]
Pr_l	2.31	1.98	1.76	1.61	1.51	1.43	1.60	1.82	2.85		[12]
Pr_g	0.79	0.82	0.83	0.84	0.91	1.06	1.24	1.59	2.12		[12]
σ , mN/m	9.64	8.29	7.26	6.22	5.22	3.34	2.45	1.62	0.88		[54]
$\beta_{e,l}$, K ⁻¹	5.5	6.0	6.6	7.3	8.4	12.5	16.0	21.5	33.0		[10]

AMMONIA

Chemical formula: NH₃
 Molecular weight: 17.032
 Normal boiling point: 239.75 K
 Melting point: 195.45 K

Critical temperature: 405.55 K
 Critical pressure: 11290 kPa
 Critical density: 235 kg/m³

T_{sat} , K	239.75	250	270	290	310	330	350	370	390	400	
p_{sat} , kPa	101.3	165.4	381.9	775.3	1424.9	2 422	3870	5 891	8606	10 280	[1]
ρ_l , kg/m ³	682	669	643	615	584	551	512	466	400	344	[1]
ρ_g , kg/m ³	0.86	1.41	3.09	6.08	11.0	18.9	31.5	52.6	93.3	137	[1]
h_l , kJ/kg	808.0	854.0	945.7	1 039.6	1 135.7	1 235.7	1 341.9	1 451.5	1 591.4	1 675.3	[1]
h_g , kJ/kg	2176	2 192	2 219	2 240	2 251	2 255	2 251	2 202	2 099	1 982	[1]
$\Delta h_{g,l}$, kJ/kg	1368	1 338	1 213	1 200	1 115	1 019	899	744	508	307	[1]
$c_{p,l}$, kJ/(kg K)	4.472	4.513	4.585	4.649	4.857	5.066	5.401	5.861	7.74		131
$c_{p,g}$, kJ/(kg K)	2.12	2.32	2.69	3.04	3.44	3.90	4.62	6.21	8.07		[1, 9]
η_l , μ Ns/m ²	285	246	190	152	125	105	88.5	70.2	50.7	39.5	[4]
η_g , μ Ns/m ²	9.25	9.59	10.30	11.05	11.86	12.74	13.75	15.06	17.15	19.5	[1, 41]
λ_l , (mW/m ²)/(K/m)	6 14	592	569	501	456	411	365	320	275	252	[2]
λ_g , (mW/m ²)/(K/m)	18.8	19.8	22.7	25.2	28.9	34.3	39.5	50.4	69.2	79.4	[2, 16]
Pr_l	2.06	1.88	1.58	1.39	1.36	1.32	1.34	1.41	1.43		[12]
Pr_g	1.04	1.11	1.17	1.25	1.31	1.34	1.49	1.70	1.86		[12]
σ , mN/m	33.9	31.5	26.9	22.4	18.0	13.7	9.60	5.74	2.21	0.68	[6]
$\beta_{e,l}$, K ⁻¹	1.90	1.98	2.22	2.63	3.18	4.01	5.50	8.75	19.7	29.2	[10]

ARGON

Chemical formula: Ar
 Molecular weight: 39.944
 Normal boiling point: 87.29 K
 Melting point: 83.78 K

Critical temperature: 150.86 K
 Critical pressure: 898 kPa
 Critical density: 536 kg/m³

T_{sat} , K	87.29	94.4	101.4	108.5	115.5	122.6	129.7	136.7	143.8	150.9	
p_{sat} , kPa	101.3	201.6	362.2	601.5	938.2	1393	1987	2738	3702	4898	[1]
ρ_L , kg/m ³	1	393	1348	1301	1251	1197	1137	1068	986.7	877.6	535.6 [1]
ρ_g , kg/m ³		5.18	10.9	18.6	30.2	46.4	68.9	100.2	146.8	222.4	535.6 [1]
h_L , kJ/kg		-116.1	-108.8	-101.1	-92.9	-84.2	-74.9	-64.5	-53.0	-40.2	-2.4 [1]
h_g , kJ/kg		43.5	45.8	47.6	48.7	49.0	48.2	46.0	41.7	33.3	-2.4 [1]
$\Delta h_{g,L}$, kJ/kg		159.6	154.6	148.9	141.6	133.2	123.1	110.6	94.7	73.5	[1]
$c_{p,L}$, kJ/(kg K)		1.083	1.168	1.200	1.218	1.257	1.358	1.559	1.923	2.011	[3, 9]
$c_{p,g}$, kJ/(kg K)	0.5	4.8	0.569	0.626	0.665	0.745	0.866	1.067	1.509	2.951	[9]
η_L , $\mu\text{Ns/m}^2$		260.5	211.9	176.6	150.8	131.1	116.1	101.7	84.2	63.9	27.9 [4]
η_g , $\mu\text{Ns/m}^2$		7.43	8.04	8.69	9.39	10.2	10.5	12.1	13.6	15.8	21.9 [4]
λ_L , (mW/m ²)/(K/m)	123.2	114.9	106.5	98.7	90.1	81.1	71.9	63.4	53.6	30	[2]
λ_g , (mW/m ²)/(K/m)	6.09	6.63	1.23	7.92	8.70	9.67	11.1	12.9	15.4	30	[9]
Pr_L	2.29	2.15	1.99	1.86	1.83	1.94	2.21	2.55	2.40		[12]
Pr_g	0.67	0.69	0.75	0.79	0.87	0.94	1.16	1.59	3.03		[12]
σ , mN/m	14.50	12.77	11.28	9.35	7.73	6.18	4.71	3.34	2.61	1.75	[6]
$\beta_{e,L}$, K^{-1}	4.58	5.01	5.50	6.41	7.80	9.61	12.6	16.8	23.1	41.8	[10]

CARBON DIOXIDE

Chemical formula: CO₂
 Molecular weight: 44.011
 Normal boiling point: 194.65 K
 Melting point: 216.55 K

Critical temperature: 304.19 K
 Critical pressure: 7382 kPa
 Critical density: 468 kg/m³

T_{sat} , K	216.55	230	240	250	260	270	280	290	300	304.19	
p_{sat} , kPa	518	891	1282	1787	2421	3203	4159	5315	6712	7382	[1]
ρ_L , kg/m ³	1179	1130	1089	1046	998	944	883	805	676	468	[1]
ρ_g , kg/m ³	15.8	20.8	32.7	45.9	63.6	88.6	121	172	268	468	[1]
h_L , kJ/kg	-206.2	-181.5	-162.5	-142.6	-121.9	-99.6	-75.7	-47.6	-10.8	42.8	[1]
h_g , kJ/kg	141.1	148.5	151.7	151.1	148.6	142.9	134.9	122.8	96.3	42.8	[1]
$\Delta h_{g,L}$, kJ/kg	347.3	330.0	314.2	293.1	270.5	242.5	210.6	170.4	107.1		[1]
$c_{p,L}$, kJ/(kg K)	2.15	2.08	2.09	2.13	2.24	2.42	2.76	3.63	7.69		[9, 1]
$c_{p,g}$, kJ/(kg K)	0.89	0.98	1.10	1.20	1.42	1.64	1.94	3.03	9.25		[9, 1]
η_L , $\mu\text{Ns/m}^2$	250	200	166	138	117	102	90.8	79.0	59.6	31.6	[9, 4]
η_g , $\mu\text{Ns/m}^2$	11.0	12.0	12.7	13.5	14.3	15.2	16.5	18.7	22.8	31.6	[4]
λ_L , (mW/m ²)/(K/m)	177	160	146	134	122	110	98	86.1	74.1	47.5	[1, 2]
λ_g , (mW/m ²)/(K/m)	11.5	12.9	14.2	15.7	17.4	19.7	22.9	28.0	39.2	47.5	[9]
Pr_L	3.04	2.60	2.38	2.19	2.15	2.24	2.56	3.33	6.19		[12]
Pr_g	0.85	0.91	0.98	1.03	1.17	1.27	1.40	2.02	5.38		[12]
σ , mN/m	17.1	13.8	11.4	9.16	7.02	5.01	3.19	1.61	0.33		[6]
$\beta_{e,L}$, K^{-1}	2.86	3.60	4.18	4.91	6.00	7.63	10.2	18.2	57		[29]

CARBON MONOXIDE

Chemical formula: CO
 Molecular weight: 28.011
 Normal boiling point: 8 1.66 K
 Melting point: 68.16 K

Critical temperature: 133.16 K
 Critical pressure: 3 498 kPa
 Critical density: 301 kg/m³

T_{sat} , K	81.66	90	95	100	105	110	115	120	125	133.16	
p_{sat} , kPa	101.3	245	437	548	776	1070	1433	1875	2 423	3 498	[1]
ρ_{ℓ} , kg/m ³	789	751	728	702	675	646	613	574	526	301	[1]
ρ_g , kg/m ³	4.40	9.99	15.4	22.4	31.0	42.6	57.2	77.5	153	301	[1]
h_{ℓ} , kJ/kg	150.4	168.6	179.8	192.3	204.1	216.1	227.1	239.3	258.1	314.33	[1]
h_g , kJ/kg	366.0	369.7	371.2	372.9	374.3	374.6	374.0	370.9	363.7	314.33	[1]
$\Delta h_{g,\ell}$, kJ/kg	215.6	201.1	191.4	180.6	169.6	158.5	146.9	131.6	105.6		[1]
$c_{p,\ell}$, kJ/(kg K)	2.15	2.17	2.20	2.26	2.34	2.46	2.61	2.19	3.02		[5]
$c_{p,g}$, kJ/(kg K)	1.22	1.35	1.52	1.60	1.79	2.03	2.42	3.18	5.25		[13, 20]
η_{ℓ} , $\mu\text{Ns/m}^2$	154	120	105	93.5	83.9	75.9	69.1	63.3	58.3		[25]
η_g , $\mu\text{Ns/m}^2$	7.08	7.51	7.80	8.11	8.44	8.80	9.23	9.78	11.7		[26, 21]
λ_{ℓ} , (mW/m ²)/(K/m)	1 4 1	125	116	107	98.2	89.3	80.3	71.4	62.5		[2]
λ_g , (mW/m ²)/(K/m)	6. 8 9	8.22	8.93	9.71	10.5	11.5	12.6	14.0	18.4		[2, 22]
Pr_{ℓ}	2.35	2.08	1.99	1.97	2.00	2.09	2.25	2.47	2.82		[12]
Pr_g	1.25	1.23	1.33	1.34	1.44	1.55	1.77	2.22	3.34		[12]
σ , mN/m	9.47	7.73	6.71	5.71	4.13	3. 1 8	2.86	1.97	1.13		[6]
$\beta_{e,\ell}$, kK^{-1}	5.46	6.65	7.52	8.44	9.63	11.6	14.9	20.7	31		[10]

CARBON TETRACHLORIDE

Chemical formula: CCl₄
 Molecular weight: 153.8
 Normal boiling point: 349.85 K
 Melting point: 250.25 K

Critical temperature 556.35 K
 Critical pressure: 4 560 kPa
 Critical density: 588 kg/m³

T_{sat} , K	349.9	370	390	410	430	450	470	495	525	556.35	
p_{sat} , kPa	101.3	184	307	473	701	1 020	1 390	2 020	3 160	4 560	[1]
ρ_{ℓ} , kg/m ³	1484	1442	1 397	1 351	1 303	1 250	1 199	1107	989	588	[1]
ρ_g , kg/m ³	5.44	9.40	15.2	23.4	34.8	50.3	71.2	108.5	184.5	588	[62]
h_{ℓ} , kJ/kg	-3 6	-17	-1	16	38	53	72	92	123	177	[67]
h_g , kJ/kg	159	169	179	188	197	205	212	218	221	177	[30, 62, 69]
$\Delta h_{g,\ell}$, kJ/kg	195	188	180	172	159	152	140	126	98		[66]
$c_{p,\ell}$, kJ/(kg K)	0.92	0.94	0.97	1.01	1.06	1.14	1.24	1.36	1.57		[5]
$c_{p,g}$, kJ/(kg K)	0.58	0.60	0.62	0.65	0.68	0.73	0.80	0.91	1.30		[30, 62]
η_{ℓ} , $\mu\text{Ns/m}^2$	494	407	352	309	274	241	205	154	98	63	[25, 33]
η_g , $\mu\text{Ns/m}^2$	11.9	12.5	13.3	14.1	14.9	15.7	16.7	18.9	21.0	63	[1, 20]
λ_{ℓ} , (mW/m ²)/(K/m)	92	87	83	78	74	70	65	57	45	25	[1]
λ_g , (mW/m ²)/(K/m)	8.6	9.3	10.0	10.7	11.5	12.3	13.2	14.3	16.3	25	[1, 22]
Pr_{ℓ}	4.94	4.40	4.16	4.08	3.93	3.92	3.91	3.67	3.42		[12]
Pr_g	0.80	0.81	0.82	0.85	0.88	0.93	1.01	1.20	1.67		[12]
σ , mN/m	20.2	17.6	15.4	13.1	10.9	8.8	6.9	4.4	2.0		[1]
$\beta_{e,\ell}$, kK^{-1}	1.36	1.50	1.68	1.90	2.19	2.58	3.14	4.30	7.83		[10]

CHLORINE

Chemical formula: Cl,
Molecular weight: 70.914
Normal boiling point: 239.11 K
Melting point: 172.65 K

Critical temperature: 417.15 K
Critical pressure: 7 710 **kPa**
Critical density: 5 73 kg/m³

T_{sat}, K	239	261	283	305	328	350	372	394	411	416	
$P_{\text{sat}}, \text{kPa}$	101.3	241	501	928	1 575	2 501	3 769	5 452	7 036	7 634	[1]
$\rho_{\ell}, \text{kg/m}^3$	1 563	1503	1439	1 370	1 295	1213	1 116	992.1	838.9	700.8	[1]
$\rho_g, \text{kg/m}^3$	3.69	8.20	16.2	28.9	48.5	78.1	123.8	202.0	329.0	468.4	[1]
$h_{\ell}, \text{kJ/kg}$	237.7	258.8	280.5	302.6	325.6	349.9	377.0	409.7	444.2	467.3	[1]
$h_g, \text{kJ/kg}$	525.4	533.9	541.7	548.1	552.8	554.8	553.0	543.9	523.4	499.8	[1]
$\Delta h_{g,\ell}, \text{kJ/kg}$	287.7	275.1	261.2	245.5	227.2	204.9	176.0	134.2	79.2	32.5	[1]
$c_{p,\ell}, \text{kJ/(kg K)}$	0.949	0.954	0.962	0.973	1.01	1.10	1.40	1.93			[6]
$c_{p,g}, \text{kJ/(kg K)}$	0.497	0.528	0.579	0.644	0.748	0.985	1.40	1.98	4.40		[3, 20]
$\eta_{\ell}, \mu\text{Ns/m}^2$	496.5	428.6	372.6	331.3	285.5	270.5	248.5	230.0	217.6	214.2	[7]
$\eta_g, \mu\text{Ns/m}^2$	10.9	12.5	13.6	14.8	16.0	17.5	19.5	22.3	28.0	35.9	14,141
$\lambda_{\ell}, (\text{mW/m}^2)/(\text{K/m})$	163	154	143	132	120	107	93.6	76.8	59.8	48.8	[2]
$\lambda_g, (\text{mW/m}^2)/(\text{K/m})$	6.9	7.8	8.7	10.0	11.5	13.1	15.7	19.5	26.5	34.0	[2, 22]
Pr_{ℓ}	2.89	2.66	2.52	2.45	2.41	2.79	3.71	5.76			[12]
Pr_g	0.79	0.85	0.91	0.95	1.04	1.32	1.72	2.26	4.65		[12]
$\sigma, \text{mN/m}$	26.90	23.58	19.96	16.53	13.14	9.64	6.34	3.13	0.76	0.12	[6]
$\beta_{e,\ell}, \text{kK}^{-1}$	1.69	1.95	2.27	2.70	3.38	4.16	6.08	10.5	26.0		[10]

FLUORINE

Chemical formula: F₂
Molecular weight: 38.00
Normal boiling point: 85.2 K
Melting point: 53 K

Critical temperature: 144 K
Critical pressure: 5 320 **kPa**
Critical density: 5 35 kg/m³

T_{sat}, K	85.2	95	100	105	110	117.5	122.5	127.5	132.5	142.5	
$P_{\text{sat}}, \text{kPa}$	101.3	278	428	634	903	1439	1 903	2470	3 159	4 987	[1]
$\rho_{\ell}, \text{kg/m}^3$	1524	1435	1393	1 349	1 303	1 229	1 174	1112	1040	749.0	[1]
$\rho_g, \text{kg/m}^3$	8.30	14.4	21.7	31.7	44.9	72.0	97.2	130.5	176.8	378.8	[1]
$h_{\ell}, \text{kJ/kg}$	-359.8	-342.5	-333.8	-324.9	-316.1	-302.2	-292.4	-282.0	-270.9	-236.8	[1]
$h_g, \text{kJ/kg}$	-168.2	-164.2	-162.4	-161.1	-160.5	-160.9	-162.3	-165.0	-169.5	-192.4	[1]
$\Delta h_{g,\ell}, \text{kJ/kg}$	191.6	178.3	171.4	163.8	155.6	141.3	130.1	117.0	101.4	44.4	[1]
$c_{p,\ell}, \text{kJ/(kg K)}$	1.55	1.60	1.65	1.72	1.83	2.04	2.23	2.47	2.75	3.47	[3, 5]
$c_{p,g}, \text{kJ/(kg K)}$	0.795	0.881	0.945	1.03	1.14	1.35	1.60	2.22	3.61		[30, 20]
$\eta_{\ell}, \mu\text{Ns/m}^2$	237	183	163	147	133	117	108	99.8	93.0	89.5	[25]
$\eta_g, \mu\text{Ns/m}^2$	7.23	8.57	9.09	9.62	10.2	11.2	11.9	12.9	14.2	21.4	14,141
$\lambda_{\ell}, (\text{mW/m}^2)/(\text{K/m})$	158	143	135	128	121	114	102	94	85	53	[2]
$\lambda_g, (\text{mW/m}^2)/(\text{K/m})$	7.0	8.3	8.9	9.5	10.5	11.8	13.2	15.0	17.0	26.5	[2, 22]
Pr_{ℓ}	2.33	2.77	1.99	1.98	2.01	2.09	2.36	2.62	3.01	5.86	[12]
Pr_g	0.82	0.91	0.97	1.04	1.11	1.28	1.44	1.91	3.01		[12]
$\sigma, \text{mN/m}$	14.25	12.13	11.03	9.92	8.79	7.06	5.87	3.91	3.38	0.56	[6]
$\beta_{e,\ell}, \text{kK}^{-1}$	6.30	6.59	6.88	7.55	8.52	10.6	12.5	16.2	23.2		[10]

HELIUM

Chemical formula: He
 Molecular weight: 4.002 6
 Normal boiling point: 4.21 K
 Melting point: 0.95 K

Critical temperature: 5.19 K
 Critical pressure: 2 290 kPa
 Critical density: 69.3 kg/m³

T_{sat}, K	4.21	4.3	4.4	4.5	4.6	4.7	4.8	4.9	5.0	5.19	
$p_{\text{sat}}, \text{kPa}$	101.3	111	120	132	144	157	169	184	199	229	[1]
$\rho_{\text{L}}, \text{kg/m}^3$	125.0	123.6	122.0	119.5	117.0	114.4	111.0	106.5	101.0	69.3	[1]
$\rho_{\text{G}}, \text{kg/m}^3$	11.58	12.43	13.13	14.12	15.07	16.08	16.95	18.08	19.16		[111]
$h_{\text{L}}, \text{kJ/kg}$	0.00	0.42	0.50	0.53	0.57	0.62	0.69	0.82	1.02		[95]
$h_{\text{G}}, \text{kJ/kg}$	20.9	20.72	20.20	19.33	18.57	17.42	16.29	14.62	13.62		[85]
$\Delta h_{\text{g,L}}, \text{kJ/kg}$	20.9	20.3	19.7	18.8	18.0	16.8	15.6	13.8	12.0		[1]
$c_{p,\text{L}}, \text{kJ/(kg K)}$	4.48	4.77	5.11	5.53	5.94	6.57	7.53	9.08	11.5		[1]
$c_{p,\text{G}}, \text{kJ/(kg K)}$	5.19	5.19	5.19	5.19	5.19	5.19	5.19	5.19	5.19		[30, 92]
$\eta_{\text{L}}, \mu\text{Ns/m}^2$	36.5	36.3	36.1	36.0	35.8	35.5	35.4	35.1	34.9		[25]
$\eta_{\text{G}}, \mu\text{Ns/m}^2$	1.09	1.11	1.13	1.16	1.18	1.20	1.22	1.25	1.27	1.31	14,931
$\lambda_{\text{L}}, (\text{mW/m}^2)/(\text{K/m})$	31.2	32.4	33.9	35.4	37.0	38.7	40.5	42.3	44.3		[7]
$\lambda_{\text{G}}, (\text{mW/m}^2)/(\text{K/m})$	8.3	8.45	8.60	8.79	8.95	9.1	9.28	9.43	9.62		[31, 93]
Pr_{L}	5.23	5.37	5.44	5.62	5.75	6.19	6.58	7.95	9.06		[12]
Pr_{G}	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.69	0.69		[12, 93]
$\sigma, \text{mN/m}$	0.111	0.099	0.087	0.075	0.063	0.061	0.040	0.028	0.019		[6]
$\beta_{e,\text{L}}, \text{kK}^{-1}$	117	144	177	214	256	306	384	528	806		[10]

HYDROGEN

Chemical formula: H₂
 Molecular weight: 2.016 0
 Normal boiling point: 20.38 K
 Melting point: 13.95 K

Critical temperature: 33.23 K
 Critical pressure: 1 316 kPa
 Critical density: 3 1.6 kg/m³

T_{sat}, K	20.38	21	23	25	27	29	30	31	32	33.23	
$p_{\text{sat}}, \text{kPa}$	101.3	121	204	321	479	685	808	946	1 100	1 316	[1]
$\rho_{\text{L}}, \text{kg/m}^3$	71.1	70.4	67.9	65.0	61.6	57.4	54.9	51.7	47.5	31.6	[1]
$\rho_{\text{G}}, \text{kg/m}^3$	1.31	1.56	2.49	3.88	5.81	8.60	10.5	13.0	16.6	31.6	[1]
$h_{\text{L}}, \text{kJ/kg}$	262	268	291	317	348	384	406	431	463	561	[1]
$h_{\text{G}}, \text{kJ/kg}$	718	721	729	732	730	719	710 6 9 4	671	671	561	[1]
$\Delta h_{\text{g,L}}, \text{kJ/kg}$	456	453	438	415	382	335	304	263	208		[1]
$c_{p,\text{L}}, \text{kJ/(kg K)}$	9.74	10.2	11.8	13.7	16.4	21.1	25.5	33.8	55.8		[1]
$c_{p,\text{G}}, \text{kJ/(kg K)}$	11.7	11.9	13.0	14.6	17.5	23.3	28.9	39.7	69.1		[1]
$\eta_{\text{L}}, \mu\text{Ns/m}^2$	12.7	12.0	10.5	9.05	7.84	6.76	6.27	5.67	5.00	3.38	[1]
$\eta_{\text{G}}, \mu\text{Ns/m}^2$	1.12	1.17	1.30	1.43	1.56	1.74	1.86	2.00	2.19	3.38	[1]
$\lambda_{\text{L}}, (\text{mW/m}^2)/(\text{K/m})$	119	121	126	127	122	112	106	100	91	60	[3]
$\lambda_{\text{G}}, (\text{mW/m}^2)/(\text{K/m})$	16.3	16.9	19.2	22	25	29	31	35	40	60	[3]
Pr_{L}	1.04	1.02	0.99	0.98	1.05	1.27	1.51	1.92	3.07		[12]
Pr_{G}	0.80	0.82	0.88	0.95	1.09	1.40	1.73	2.27	3.78		[12]
$\sigma, \text{mN/m}$	1.92	1.81	1.47	1.13	0.796	0.483	0.333	0.207	0.106		[1]
$\beta_{e,\text{L}}, \text{kK}^{-1}$	15.9	16.8	20.6	26.3	35.1	52.0	68.4	95.3	172.9		[10]

HYDROGEN CHLORIDE

Chemical formula: **HCl**
Molecular weight: 36.461
Normal boiling point: 188.05 K
Melting point: 158.93 K

Critical temperature: 324.6 K
Critical pressure: 8 309 **kPa**
Critical density: 450 **kg/m³**

T_{sat} , K	188.05	200	215	230	245	260	275	290	305	324.65	
p_{sat} , kPa	101.3	180	370	670	1 100	1 800	2 700	3 800	5 500	8 309	[45]
ρ_L , kg/m ³	1 190	1 155	1 115	1 070	1 020	970	925	845	755	450	[45]
ρ_g , kg/m ³	2.5	5	10	15	25	40	55	90	140	450	[45]
h_L , kJ/kg	0.0	20	45	71	99	130	164	203	247		[83]
h_g , kJ/kg	442	452	461	467	473	478	480	478	465		1841
$\Delta h_{g,L}$, kJ/kg	442	432	416	396	374	348	316	275	218		[66]
$c_{p,L}$, kJ/(kg K)	1.61	1.66	1.74	1.84	1.95	2.15	2.34	2.67	3.28		[5, 70]
$c_{p,g}$, kJ/(kg K)	0.85	0.87	0.91	0.96	1.04	1.16	1.36	1.74	2.74		[30, 62]
η_L , $\mu\text{Ns/m}^2$	407	332	259	204	160	126	101	77	60	34	[25, 45]
η_g , $\mu\text{Ns/m}^2$	9.0	9.6	10.4	11.2	12.1	13.0	14.1	15.1	16.8	34	[26, 45, 21]
λ_L , (mW/m ²)/(K/m)	337	323	305	285	264	242	219	195	169	61	[7, 45]
λ_g , (mW/m ²)/(K/m)	8.6	9.3	10.5	12.0	13.5	15.6	17.8	21.6	26.9	61	[31, 22, 107]
Pr_L	1.94	1.71	1.48	1.32	1.18	1.12	1.08	1.05	1.16		[12]
Pr_g	0.89	0.90	0.90	0.90	0.93	0.97	1.06	1.22	1.71		[12]
σ , mN/m	23.2	21.0	18.3	15.5	12.9	10.2	7.7	5.2	2.8		[6]
$\beta_{e,L}$, K^{-1}	2.31	2.49	2.72	3.30	3.81	4.00	5.91	9.52	30.55		[10]

HYDROGEN FLUORIDE

Chemical formula: **HF**
Molecular weight: 20.063
Normal boiling point: 292.69 K
Melting point : 190 K

Critical temperature: 461.15 K
Critical pressure: 6 485 **kPa**
Critical density: 290.0 **kg/m³**

T_{sat} , K	292.69	305	325	345	365	385	405	425	445	461.15	
p_{sat} , kPa	101.3	152	285	500	820	1 320	2 100	3 150	4 800	6 490	[45]
ρ_L , kg/m ³	968	945	905	862	816	765	710	640	545	290	[45]
ρ_g , kg/m ³	2.0	3.5	5.0	10.0	14.0	20	28	45	88	290	[45]
h_L , kJ/kg	0.0	37.9	101.6	168	239	316	400	493	598		1841
h_g , kJ/kg	330	407.9	536.6	653	769	896	1 010	1068	993		[85]
$\Delta h_{g,L}$, kJ/kg	330	370	435	485	530	580	610	575	395		[66]
$c_{p,L}$, kJ/(kg K)	3.04	3.12	3.26	3.44	3.68	4.00	4.41	4.92	5.56		[5]
$c_{p,g}$, kJ/(kg K)	1.46	1.46	1.46	1.46	1.46	1.46	1.46	1.46	1.46		[30, 92]
η_L , $\mu\text{Ns/m}^2$	215	191	161	139	121	106	93	81.6	71.2	39.8	[25, 45]
η_g , $\mu\text{Ns/m}^2$	10.9	12.2	13.5	14.5	15.4	16.3	17.2	18.1	18.9	39.8	[26, 45, 93]
λ_L , (mW/m ²)/(K/m)	402	387	362	335	310	283	255	227	199		[7, 45]
λ_g , (mW/m ²)/(K/m)	21.0	21.8	23.0	24.3	25.6	26.9	28.3	29.6	30.9	32.0	[31, 45, 93]
Pr_L	1.63	1.54	1.45	1.43	1.44	1.50	1.61	1.77	1.99	2.22	[12]
Pr_g	0.76	0.82	0.85	0.87	0.88	0.88	0.88	0.89	0.89		[12, 93]
σ , mN/m	8.65	7.85	6.75	5.6	4.6	3.5	2.5	1.6	0.7		[6]
$\beta_{e,L}$, K^{-1}	1.93	2.13	2.45	2.91	3.54	4.40	6.08	9.9s	27.6		[10]

HYDROGEN SULFIDEChemical formula: H_2S

Molecular weight: 34.08

Normal boiling point: 212.8 K

Melting point: 187.6 K

Critical temperature: 373.15 K

Critical pressure: 8 937 kPa

Critical density: 346 kg/m³

T_{sat} , K	212.8	220	240	260	280	300	320	340	360	373.15	
p_{sat} , kPa	101.3	140	325	680	1020	2000	3 250	4890	7 050	8937	[45]
ρ_{ℓ} , kg/m ³	965	955	915	875	830	780	720	650	565	346	[4]
ρ_g , kg/m ³	2.0	2.6	5.5	11.0	21.0	35.0	55.0	95.0	160.0	346	[45]
h_{ℓ} , kJ/kg	-356	-341	-301	-256	-207	-161	-104	-42	45	68	[67]
h_g , kJ/kg	199	204	219	230	239	244	241	228	190	68	[63, 62, 69]
$\Delta h_{g,\ell}$, kJ/kg	555	545	520	485	445	405	345	270	145		[45]
$c_{p,\ell}$, kJ/(kg K)	1.83	1.85	1.91	2.00	2.13	2.35	2.64	3.10	4.38		[70]
$c_{p,g}$, kJ/(kg K)	1.02	1.03	1.08	1.16	1.28	1.45	1.77	2.48	6.45		[45, 63, 62]
η_{ℓ} , $\mu\text{Ns/m}^2$	423	378	272	205	162	130	110	87	66	40.5	[45, 33]
η_g , $\mu\text{Ns/m}^2$	9.2	9.6	10.5	11.4	12.4	13.5	14.8	16.5	19.2	40.5	[45, 21]
λ_{ℓ} , (mW/m ²)/(K/m)	233	224	199	175	153	131	107	85	62	49.5	[45, 22]
λ_g , (mW/m ²)/(K/m)	9.1	9.6	11.1	12.9	14.7	17.0	19.8	24.1	30.5	49.5	[45, 22, 107]
Pr_{ℓ}	3.32	3.12	2.61	2.34	2.26	2.33	2.71	3.17	4.66		[12]
Pr_g	1.03	1.03	1.02	1.03	1.08	1.15	1.32	1.70	4.06		[12]
σ , mN/m	29.0	27.5	23.5	19.6	16.0	12.5	9.2	5.5	2.2		[45]
$\beta_{e,\ell}$, kK^{-1}	1.86	1.98	2.31	2.69	3.34	4.40	6.10	8.99	31.5		[10]

MERCURY

Chemical formula: Hg

Molecular weight: 200.5 1

Normal boiling point: 630.1 K

Melting point : 234.32 K

Critical temperature: 1 763.2 K

Critical pressure: 15 1 000 kPa

Critical density: 5 500 kg/m³

T_{sat} , K	630.1	650	700	750	800	850	900	950	1000	1050	
p_{sat} , kPa	101.3	145	316 ^a	620	1 120	1880	2990	4530	6580	9230	[1]
ρ_{ℓ} , kg/m ³	12 737	12688	12 567	12 444	12 318	12 190	12059	11927	11791	11650	[1]
ρ_g , kg/m ³	3.91	5.37	10.9	20.1	34.2	54.6	82.7	119.9	167.7	227.3	[1]
h_{ℓ} , kJ/kg	91.8	94.5	101.3	108.2	115.2	122.3	129.5	136.9	144.4	153.8	[1]
h_g , kJ/kg	386.7	388.7	393.6	398.4	403.0	407.4	411.6	415.5	419.1	423.0	[1]
$\Delta h_{g,\ell}$, kJ/kg	294.9	294.2	292.3	290.2	287.8	285.1	282.1	278.6	274.7	269.2	[1]
$c_{p,\ell}$, kJ/(kg K)	0.136	0.136	0.137	0.138	0.140	0.142	0.144	0.146	0.149	0.153	[1]
$c_{p,g}$, kJ/(kg K)	0.104	0.104	0.105	0.106	0.107	0.108	0.109	0.111	0.113	0.116	[1]
η_{ℓ} , $\mu\text{Ns/m}^2$	884	870	841	816	794	776	760	746	736	723	[1]
η_g , $\mu\text{Ns/m}^2$	61.7	63.5	68.6	73.5	78.4	83.5	88.4	93.2	98.0	103.0	[1]
λ_{ℓ} , (mW/m ²)/(K/m)	121.9	123.6	128.0	131.9	135.1	137.8	141.8	144.5	146.9	147.9	[1, 48]
λ_g , (mW/m ²)/(K/m)	10.4	10.8	11.7	12.6	13.5	14.4	15.3	16.2	17.2	18.1	[1]
Pr_{ℓ}	0.987	0.957	0.900	0.854	0.823	0.800	0.772	0.754	0.744	0.748	[12]
Pr_g	0.617	0.612	0.616	0.618	0.621	0.626	0.630	0.637	0.644	0.660	[12]
σ , mN/m											[50]
$\beta_{e,\ell}$, kK^{-1}	0.194	0.193	0.195	0.203	0.212	0.221	0.230	0.241	0.253	0.269	[10]

NEON

Chemical formula: Ne
Molecular weight: 20.183
Normal boiling point: 27.09 K
Melting point: 24.5 K

Critical temperature: 44.4 K
Critical pressure: 2 654 kPa
Critical density: 483 kg/m³

T_{sat} , K	27.1	29	31	33	35	37	39	41	43	44.4	
p_{sat} , kPa	101.3	174	284	439	646	916	1 260	1 688	2 216	2 654	[1]
ρ_L , kg/m ³	1 205	1 170	1 131	1 089	1 043	992	932	859	754	483	[1]
ρ_g , kg/m ³	9.57	15.7	25.0	38.0	56.0	80.8	115.3	164.5	243.5	483	[1]
h_L , kJ/kg	5.01	9.00	13.38	17.96	22.74	27.70	32.93	38.67	46.32		[1]
h_g , kJ/kg	91.11	92.23	93.00	93.27	92.94	91.85	89.83	86.58	81.13		[1]
$\Delta h_{g,L}$, kJ/kg	86.1	83.2	79.6	75.3	70.2	64.2	56.9	47.9	34.8		[1]
$c_{p,L}$, kJ/(kg K)	1.87	1.92	1.97	2.05	2.14	2.29	2.49	2.77	3.23		[5]
$c_{p,g}$, kJ/(kg K)	1.31	1.42	1.61	1.84	2.02	2.42	3.06	4.45	8.08		[3, 20, 371]
η_L , $\mu\text{Ns/m}^2$	127	105	92.5	77.9	65.9	56.6	47.3	38.6	27.8	16.7	[1, 4]
η_g , $\mu\text{Ns/m}^2$	4.63	5.04	5.43	5.83	6.12	6.82	7.43	8.47	11.9	16.7	[4]
λ_L , (mW/m ²)/(K/m)	113	110	108	102	96.5	88.6	78.9	67.3	50.3	33	[2]
λ_g , (mW/m ²)/(K/m)	7.7	8.5	9.3	10.2	11.1	12.4	13.9	16.0	22.8	33	[2]
Pr_L	2.10	1.83	1.69	1.57	1.46	1.46	1.49	1.59	1.69		[12]
Pr_g	0.79	0.84	0.94	1.05	1.11	1.33	1.64	2.36	4.22		[12]
σ , mN/m	4.78	4.15	3.50	2.87	2.26	1.69	1.15	0.65	0.20		[1, 6]
$\beta_{e,L}$, kK^{-1}	1.47	1.66	1.91	2.23	2.68	3.32	4.47	7.10	31.0		[10]

NITROGEN

Chemical formula: N₂
Molecular weight: 28.016
Normal boiling point: 77.35 K
Melting point: 63.15 K

Critical temperature: 126.25 K
Critical pressure: 3 396 kPa
Critical density: 304 kg/m³

T_{sat} , K	77.35	85	90	95	100	105	110	115	120	126	
p_{sat} , kPa	101.3	290	360	540	778	1 083	1 467	1 940	2 515	3 357	[1]
ρ_L , kg/m ³	807.10	771.01	746.27	719.42	691.08	660.5	626.17	583.43	528.54	379.22	[1]
ρ_g , kg/m ³	4.621	9.833	15.087	22.286	31.989	44.284	62.578	87.184	124.517	237.925	[1]
h_L , kJ/kg	-120.8	-105.7	-95.6	-85.2	-74.5	-63.8	-51.4	-38.1	-21.4	17.4	[1]
h_g , kJ/kg	76.8	82.3	85.0	86.8	87.7	87.4	85.6	81.8	74.3	49.5	[1]
$\Delta h_{g,L}$, kJ/kg	197.6	188.0	180.5	172.2	162.2	150.7	137.0	119.9	95.7	32.1	[1]
$c_{p,L}$, kJ/(kg K)	2.064	2.096	2.140	2.211	2.311	2.467	2.711	3.180	4.347		[9]
$c_{p,g}$, kJ/(kg K)	1.123	1.192	1.258	1.350	1.474	1.666	1.975	2.586	4.136		[9]
η_L , $\mu\text{Ns/m}^2$	163	127	110	97.2	86.9	78.5	70.8	59.9	48.4	19.1	[4]
η_g , $\mu\text{Ns/m}^2$	5.41	5.60	6.36	6.80	7.28	7.82	8.42	9.25	10.68	19.1	[4, 9]
λ_L , (mW/m ²)/(K/m)	136.7	122.9	112.0	104.0	95.5	88.0	80.2	70.4	62.8	52.8	[1, 9]
λ_g , (mW/m ²)/(K/m)	7.54	8.18	9.04	9.77	10.60	11.69	14.50	20.76	30.91	51.11	[9]
Pr_L	2.46	2.17	2.10	2.07	2.10	2.20	2.39	2.71	3.35		[12]
Pr_g	0.81	0.82	0.89	0.94	1.01	1.11	1.15	1.16	1.43		[12]
σ , mN/m	8.85	7.20	6.16	4.59	3.67	2.79	1.98	1.18	0.52	0.01	[27, 28]
$\beta_{e,L}$, kK^{-1}	5.65	6.46	7.26	8.47	9.69	12.1	15.7	23.0	37.5		[10]

OXYGEN

Chemical formula: O₂
Molecular weight: 32.00
Normal boiling point: 90.18 K
Melting point: 54.35 K

Critical temperature: 154.77 K
Critical pressure: 5 090 kPa
Critical density: 405 kg/m³

T_{sat}^* , K	90.18	97	104	111	118	125	132	1 4 0	146	154	
p_{sat} , kPa	101.3	196	352	583	908	1 348	1 924	2 782	3 591	3 939	[1]
ρ_L , kg/m ³	1135.72	1 102.05	1065.07	1025.64	982.32	934.58	880.28	808.41	737.56	557.10	[1]
ρ_g , kg/m ³	4.48	8.23	14.14	22.79	35.03	52.05	75.81	116.12	163.34	304.41	[1]
h_L , kJ/kg	-133.4	-122.1	-110.3	-98.2	-85.4	-71.8	-57.8	-38.9	-23.2	10.6	[1]
h_g , kJ/kg	78.9	83.8	88.0	91.2	93.3	93.9	92.8	88.4	81.4	56.7	[1]
$\Delta h_{g,L}$, kJ/kg	212.3	205.9	198.3	189.4	178.7	165.7	150.1	127.3	104.6	46.1	[1]
$c_{p,L}$, kJ/(kg K)	1.63	1.66	1.70	1.76	1.86	2.00	2.22	2.63	3.28		[1]
$c_{p,g}$, kJ/(kg K)	0.96	1.00	1.05	1.12	1.23	1.36	1.68	2.27	3.63		[9]
η_L , $\mu\text{Ns/m}^2$	195.83	161.75	136.55	116.80	101.20	89.00	80.15	69.66	60.65	42.48	[9]
η_g , $\mu\text{Ns/m}^2$	6.85	7.50	8.35	9.36	10.6	11.24	13.35	15.8	18.5	26.9	[9]
λ_L , (mW/m ²)/(K/m)	14.8	139	130	121	111	102	92.5	82.0	71.2		[1]
λ_g , (mW/m ²)/(K/m)	8.5	9.5	10.5	11.7	13.4	14.8	16.9	20.1	23.6	35.2	[9]
Pr_L	2.16	1.93	1.79	1.70	1.70	1.75	1.92	2.23	2.79		[12]
Pr_g	0.77	0.79	0.84	0.90	0.97	1.03	1.33	1.78	2.85	19.93	[12]
σ , mN/m	13.19	11.53	9.88	8.27	6.71	5.20	3.77	2.23	1.18	0.40	[6]
$\beta_{e,L}$, K^{-1}	4.26	4.71	5.39	6.30	7.38	9.65	11.9	17.6	29.0	545.0	[10]

WATER

Chemical formula: H₂O
Molecular weight: 18.015 6
Normal boiling point: 373.15 K
Melting point: 273.15 K

Critical temperature: 647.3 K
Critical pressure: 22 129 kPa
Critical density: 3 15 kg/m³

T_{sat}^* , K	373.15	400	430	460	490	520	550	580	610	647.3	
p_{sat} , kPa	101.3	247	571	1 172	2 185	3 773	6 124	9 460	14 044	22 129	[57]
ρ_L , kg/m ³	958.3	937.5	910.3	879.4	844.3	803.8	756.1	697.2	619.5	315	[44]
ρ_g , kg/m ³	0.597	1.370	3.020	5.975	10.95	18.90	31.52	51.85	87.5	315	[44]
h_L , kJ/kg	419.10	533.0	662.1	793.5	929.4	1 070.9	1 220.5	1 384.0	1572.9	2 100	[44]
h_g , kJ/kg	2 675.8	2 716	2 754.9	2 783.9	2 800.9	2 801.9	2 783.1	2 734.3	2 637.1	2 100	[44]
$\Delta h_{g,L}$, kJ/kg	2 256.7	2 183	2 092.8	1 990.4	1 871.5	1 731.0	1 562.6	1 350.3	1064.2	0.0	[44]
$c_{p,L}$, kJ/(kg K)	4.22	4.24	4.28	4.45	4.60	4.84	5.07	5.70	8.12		[44]
$c_{p,g}$, kJ/(kg K)	2.03	2.16	2.35	2.70	3.17	3.84	4.87	6.71	11.2		[1]
η_L , $\mu\text{Ns/m}^2$	277.53	218.9	175.73	147.24	126.6	111.05	99.21	89.40	78.60	23.1	[44]
η_g , $\mu\text{Ns/m}^2$	12.55	13.57	14.716	15.86	17.00	18.14	19.33	20.51	21.68	23.1	[44]
λ_L , (mW/m ²)/(K/m)	679.0	685.7	683.3	671.3	646.0	618.3	580.9	536.6	464.0	914	[57]
λ_g , (mW/m ²)/(K/m)	25.0	28.1	31.6	36.6	42.3	50.1	60.2	77.3	111.4	914	[57]
Pr_L	1.72	1.35	1.10	0.98	0.90	0.87	0.87	0.950	1.38		[12]
Pr_g	1.02	1.04	1.09	1.17	1.27	1.39	1.56	1.78	2.17		[12]
σ , mN/m	58.91	53.50	47.16	40.66	33.90	26.96	19.66	12.71	6.26	0.0	[1]
$\beta_{e,L}$, K^{-1}	0.78	0.91	1.02	1.24	1.89	2.00	2.70	3.92	7.85		[10]

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where $n = 0.38$

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where V_{mp} = liquid volume at melting point.

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5.5.2

Properties of superheated gases

R. N. Maddox

■ The tables in this section provide information on several gases of industrial importance. In the tables, v is specific volume in m^3/kg , h is enthalpy in kJ/kg , s is en-

trophy in $\text{kJ}/(\text{kg K})$, and u is internal energy in kJ/kg . These tables were excerpted from a very helpful manual, "Thermodynamic Properties in SI" by W. C. Reynolds[1].

Table 1 Properties of gaseous helium-4^a

Pressure, MPa	Property	Value at different temperatures, K							
		40	70	100	300	500	700	1000	1500
0.101 325	$v, \text{m}^3/\text{kg}$	0.821 9	1.438	2.053	6.153	10.25	14.35	20.50	30.75
	$h, \text{kJ}/\text{kg}$	219.62	375.63	531.50	1570.19	2 608.80	3 647.41	5 205.32	7 801.84
	$s, \text{kJ}/(\text{kg K})$	19.465 0	22.375 5	24.228 6	29.934 3	32.587 1	34.334 4	36.186 6	38.292 2
0.20	$v, \text{m}^3/\text{kg}$	0.417 3	0.729 8	1.042	3.119	5.196	7.273	10.39	15.58
	$h, \text{kJ}/\text{kg}$	219.59	375.81	531.75	1570.51	2 609.12	3 647.72	5 205.62	7 802.12
	$s, \text{kJ}/(\text{kg K})$	18.047 0	20.961 6	22.815 7	28.522 0	31.174 7	32.922 0	34.774 2	36.879 8
0.50	$v, \text{m}^3/\text{kg}$	0.168 1	0.293 6	0.418 4	1.249	2.080	2.911	4.157	6.234
	$h, \text{kJ}/\text{kg}$	219.49	376.35	532.51	1571.51	2 610.10	3 648.68	5 206.54	7 802.99
	$s, \text{kJ}/(\text{kg K})$	16.127 1	19.054 2	20.911 0	26.619 0	29.271 7	31.018 9	32.871 1	34.976 6
1.0	$v, \text{m}^3/\text{kg}$	0.085 00	0.148 1	0.210 7	0.626 1	1.041	1.457	2.080	3.118
	$h, \text{kJ}/\text{kg}$	219.35	377.25	533.79	1573.16	2 611.74	3 650.27	5 208.07	7 804.45
	$s, \text{kJ}/(\text{kg K})$	14.660 0	17.607 6	19.469 0	25.179 7	27.832 3	29.579 5	31.431 6	33.537 1
2.0	$v, \text{m}^3/\text{kg}$	0.043 50	0.075 44	0.106 8	0.314 6	0.522 1	0.729 6	1.041	1.560
	$h, \text{kJ}/\text{kg}$	219.24	379.06	536.33	1576.46	2 615.00	3 653.45	5 211.14	7 807.34
	$s, \text{kJ}/(\text{kg K})$	13.169 0	16.154 6	18.024 7	23.740 9	26.393 5	28.140 6	29.992 5	32.097 9
4.0	$v, \text{m}^3/\text{kg}$	0.022 88	0.039 10	0.054 90	0.158 8	0.262 4	0.366 1	0.521 6	0.781 0
	$h, \text{kJ}/\text{kg}$	219.93	382.80	541.40	1583.04	2 621.51	3 659.80	5 217.25	7 813.13
	$s, \text{kJ}/(\text{kg K})$	11.645 0	14.689 7	16.576 2	22.303 2	24.955 7	26.702 5	28.554 1	30.659 2
7.0	$v, \text{m}^3/\text{kg}$	0.014 21	0.023 55	0.032 64	0.091 97	0.151 1	0.210 3	0.299 1	0.447 1
	$h, \text{kJ}/\text{kg}$	223.35	388.84	549.09	1592.86	2 631.24	3 669.28	5 226.37	7 821.77
	$s, \text{kJ}/(\text{kg K})$	10.4014	13.495 3	15.401 6	21.144 0	23.796 2	25.542 5	27.393 8	29.498 5
10	$v, \text{m}^3/\text{kg}$	0.010 83	0.017 35	0.023 74	0.065 25	0.106 6	0.148 0	0.210 0	0.313 6
	$h, \text{kJ}/\text{kg}$	228.94	395.47	556.93	1 602.63	2 640.91	3 678.71	5 235.45	7 830.37
	$s, \text{kJ}/(\text{kg K})$	9.617 3	12.729 3	14.650 2	20.406 2	23.058 3	24.804 2	26.655 0	28.759 3

(See footnote on page 5.5.2-2.)

Table 1 Properties of gaseous helium⁴ (Continued)

Pressure, MPa	Property	Value at different temperatures, K							
		40	70	100	300	500	700	1000	1500
20	$v, m^3/kg$	0.007 00	0.010 17	0.013 36	0.034 05	0.054 62	0.075 21	0.106 1	0.157 8
	$h, kJ/kg$	255.08	420.70	584.25	1634.95	2 672.86	3 709.83	5 265.41	7 858.75
	$s, kJ/(kg K)$	8.152 8	11.240 9	13.186 6	18.977 0	21.628 2	23.372 8	25.222 2	27.325 2
50	$v, m^3/kg$	0.004 65	0.005 83	0.007 08	0.015 27	0.023 36	0.031 49	0.043 74	0.064 21
	$h, kJ/kg$	350.04	506.54	670.41	1 730.11	2 766.57	3 800.87	5 352.83	7 941.55
	$s, kJ/(kg K)$	6.404 2	9.309 5	11.257 2	17.106 1	19.754 0	21.494 1	23.339 2	25.438 4
100	$v, m^3/kg$	0.003 70	0.004 27	0.004 87	0.008 90	0.012 85	0.016 83	0.022 84	0.032 94
	$h, kJ/kg$	504.52	653.87	8 14.00	1 882.29	2 917.30	3 946.88	5 492.26	8 072.99
	$s, kJ/(kg K)$	5.1517	7.922 9	9.824 6	15.718 0	18.363 0	20.095 2	21.932 4	24.025 1

^aAbridged by permission, from *Thermodynamic Properties in SI* by W. C. Reynolds, Department of Mechanical Engineering, Stanford University.

Table 2 Properties of gaseous carbon dioxide^a

Pressure, MPa	Property	Value at different temperatures, K							
		300	400	500	600	700	800	900	1000
1.0 (233.0)	$v, m^3/kg$	0.053 79	0.074 18	0.093 76	0.113 0	0.132 2	0.151 3	0.170 3	0.189 3
	$h, kJ/kg$	419.95	513.65	613.22	718.90	829.90	945.34	1 064.46	1186.61
	$s, kJ/(kg K)$	1.773 7	2.043 0	2.264 9	2.457 4	2.628 4	2.782 5	2.922 8	3.051 5
2.0 (253.6)	$v, m^3/kg$	0.025 35	0.036 40	0.046 54	0.056 38	0.066 08	0.075 71	0.085 29	0.094 84
	$h, kJ/kg$	409.41	508.45	610.01	716.73	828.37	944.25	1 063.68	1 186.07
	$s, kJ/(kg K)$	1.617 4	1.902 5	2.128 9	2.323 3	2.495 4	2.650 0	2.790 7	2.919 6
5.0 (287.5)	$v, m^3/kg$	0.007 79	0.013 74	0.018 24	0.022 41	0.026 43	0.030 39	0.034 29	0.038 17
	$h, kJ/kg$	366.98	492.26	600.43	710.37	823.93	941.10	1061.45	1 184.53
	$s, kJ/(kg K)$	1.335 1	1.699 3	1.940 7	2.141 0	2.316 0	2.472 4	2.614 1	2.743 8
10	$v, m^3/kg$		0.006 20	0.008 85	0.011 12	0.013 25	0.015 30	0.017 31	0.019 29
	$h, kJ/kg$		463.19	584.73	700.24	816.97	936.20	1 058.02	1 182.21
	$s, kJ/(kg K)$		1.512 7	1.784 6	1.995 2	2.175 1	2.334 3	2.477 7	2.608 6
20	$v, m^3/kg$		0.002 62	0.004 26	0.005 54	0.006 70	0.007 79	0.008 85	0.009 88
	$h, kJ/kg$		403.03	555.30	681.94	804.67	927.73	1 052.23	1 178.42
	$s, kJ/(kg K)$		1.263 4	1.605 4	1.836 6	2.025 8	2.190 1	2.336 7	2.469 7

^aAbridged by permission, from *Thermodynamic Properties in SI* by W. C. Reynolds, Department of Mechanical Engineering, Stanford University.

Table 3 Properties of gaseous ethane^a

Pressure, MPa	Property	Value at different temperatures, K							
		300	340	380	420	460	500	540	580
0.070 (177.8)	$v, m^3/kg$	1.180	1.340	1.499	1.658	1.816	1.975	2.134	2.292
	$h, kJ/kg$	764.36	838.62	919.15	1 006.11	1 099.55	1 199.46	1305.74	1418.27
	$s, kJ/(kg K)$	4.068 6	4.300 7	4.524 5	4.741 9	4.954 3	5.162 5	5.366 9	5.567 9
0.101 325 (184.3)	$v, m^3/kg$	0.813 2	0.924 0	1.034	1.144	1.254	1.364	1.474	1.583
	$h, kJ/kg$	763.73	838.14	918.77	1 005.80	1 099.29	1 199.24	1 305.56	1418.11
	$s, kJ/(kg K)$	3.964 8	4.197 4	4.421 4	4.639 0	4.851 6	5.059 8	5.264 3	5.465 3
0.40 (214.3)	$v, m^3/kg$	0.201 2	0.230 5	0.259 2	0.287 7	0.316 0	0.344 1	0.372 1	0.400 1
	$h, kJ/kg$	757.62	833.52	915.14	1 002.86	1 096.86	1 197.19	1 303.80	1416.60
	$s, kJ/(kg K)$	3.570 6	3.807 9	4.034 7	4.254 1	4.467 7	4.676 8	4.881 8	5.083 3
0.70 (229.8)	$v, m^3/kg$	0.112 2	0.129 6	0.146 5	0.163 2	0.179 6	0.195 8	0.212 0	0.228 1
	$h, kJ/kg$	751.24	828.77	911.44	999.88	1 094.40	1195.12	1 302.04	1415.07
	$s, kJ/(kg K)$	3.400 8	3.643 3	3.873 0	4.094 2	4.309 0	4.518 9	4.724 5	4.926 4

(See footnote on page X5.2-3.)

Table 3 Properties of gaseous ethane (Continued)

Pressure, MPa	Property	Value at different temperatures, K							
		300	340	380	420	460	500	540	580
1.0 (240.9)	$v, \text{m}^3/\text{kg}$	0.076 48	0.089 26	0.101 5	0.113 3	0.125 0	0.136 5	0.148 0	0.159 3
	$h, \text{kJ/kg}$	744.60	823.91	907.68	996.87	1091.93	1 193.05	1 300.27	1413.55
	$s, \text{kJ}/(\text{kg K})$	3.286 5	3.534 5	3.767 3	3.990 4	4.206 4	4.417 1	4.623 4	4.825 7
2.0 (265.8)	$v, \text{m}^3/\text{kg}$	0.034 5 1	0.042 05	0.048 82	0.055 20	0.061 35	0.067 36	0.073 26	0.079 10
	$h, \text{kJ/kg}$	720.03	806.77	894.73	986.63	1083.58	1 186.08	1 294.36	1408.47
	$s, \text{kJ}/(\text{kg K})$	3.035 3	3.306 7	3.551 2	3.781 1	4.001 5	4.215 1	4.423 3	4.627 1
4.0 (295.5)	$v, \text{m}^3/\text{kg}$	0.011 83	0.018 13	0.022 43	0.026 14	0.029 57	0.032 83	0.035 97	0.039 04
	$h, \text{kJ/kg}$	644.02	766.56	866.58	965.16	1 066.43	1 171.98	1 282.52	1 398.37
	$s, \text{kJ}/(\text{kg K})$	2.641 8	3.027 1	3.305 4	3.552 0	3.782 3	4.002 2	4.214 8	4.421 8
7.0	$v, \text{m}^3/\text{kg}$		0.007 27	0.011 06	0.013 74	0.016 04	0.018 12	0.020 09	0.021 97
	$h, \text{kJ/kg}$		678.32	817.80	930.66	1 039.90	1 150.64	1 264.88	1 383.51
	$s, \text{kJ}/(\text{kg K})$		2.663 7	3.053 1	3.335 7	3.584 1	3.814 9	4.034 7	4.246 6
10	$v, \text{m}^3/\text{kg}$		0.003 97	0.006 72	0.008 92	0.010 74	0.012 35	0.013 83	0.015 23
	$h, \text{kJ/kg}$		589.90	764.34	894.94	1013.29	1 129.67	1 247.78	1 369.25
	$s, \text{kJ}/(\text{kg K})$		2.357 9	2.844 6	3.1719	3.441 1	3.683 7	3.910 9	4.127 9
20	$v, \text{m}^3/\text{kg}$		0.002 77	0.003 42	0.004 29	0.005 21	0.006 09	0.006 91	0.007 69
	$h, \text{kJ/kg}$		532.36	668.78	808.21	941.97	1071.47	1 199.79	1 329.20
	$s, \text{kJ}/(\text{kg K})$		2.096 6	2.475 6	2.824 6	3.128 9	3.398 9	3.645 8	3.876 9
30	$v, \text{m}^3/\text{kg}$		0.002 52	0.002 87	0.003 32	0.003 84	0.004 38	0.004 92	0.005 44
	$h, \text{kJ/kg}$		526.36	646.92	774.99	905.97	1037.43	1 169.40	1 302.75
	$s, \text{kJ}/(\text{kg K})$		2.001 7	2.336 7	2.657 0	2.954 9	3.229 0	3.482 9	3.721 1

^aAbridged by permission, from *Thermodynamic Properties in SI* by W. C. Reynolds, Department of Mechanical Engineering, Stanford University.

Table 4 Properties of gaseous ethylene

Pressure, MPa	Property	Value at different temperatures, K							
		250	275	300	325	350	375	400	425
0.101 325 (169.4)	$v, \text{m}^3/\text{kg}$	0.723 9	0.798 3	0.872 5	0.946 4	1.020	1.094	1.167	1.241
	$h, \text{kJ/kg}$	636.60	672.44	710.12	749.81	791.63	835.64	881.87	930.30
	$s, \text{kJ}/(\text{kg K})$	3.659 2	3.795 8	3.926 9	4.053 9	4.177 8	4.299 3	4.418 6	4.536 0
0.20 (181.9)	$v, \text{m}^3/\text{kg}$	0.363 0	0.401 5	0.439 5	0.477 4	0.515 1	0.552 6	0.590 1	0.627 5
	$h, \text{kJ/kg}$	634.30	670.58	708.57	748.50	790.50	834.66	881.00	929.53
	$s, \text{kJ}/(\text{kg K})$	3.451 4	3.589 6	3.721 8	3.849 6	3.974 1	4.095 9	4.215 5	4.333 2
0.50 (202.3)	$v, \text{m}^3/\text{kg}$	0.140 6	0.156 9	0.172 8	0.188 4	0.203 9	0.219 2	0.234 4	0.249 6
	$h, \text{kJ/kg}$	627.07	664.76	703.78	744.46	787.04	831.65	878.36	927.19
	$s, \text{kJ}/(\text{kg K})$	3.159 9	3.303 6	3.439 3	3.569 5	3.695 7	3.818 8	3.939 4	4.057 7
1.0 (221.3)	$v, \text{m}^3/\text{kg}$	0.066 16	0.075 20	0.083 77	0.092 04	0.100 1	0.108 1	0.115 9	0.123 7
	$h, \text{kJ/kg}$	614.02	654.54	695.48	737.54	781.16	826.57	873.91	923.25
	$s, \text{kJ}/(\text{kg K})$	2.917 8	3.072 3	3.214 7	3.349 4	3.478 7	3.603 9	3.726 1	3.845 8
2.0 (244.3)	$v, \text{m}^3/\text{kg}$	0.028 09	0.034 02	0.039 12	0.043 79	0.048 22	0.052 49	0.056 65	0.060 72
	$h, \text{kJ/kg}$	581.93	631.43	677.50	722.94	768.96	816.15	864.87	915.31
	$s, \text{kJ}/(\text{kg K})$	2.617 6	2.806 5	2.966 8	3.112 3	3.248 7	3.378 9	3.504 7	3.627 0
5.0 (282.0)	$v, \text{m}^3/\text{kg}$			0.011 37	0.014 54	0.017 00	0.019 17	0.021 16	0.023 04
	$h, \text{kJ/kg}$			602.17	670.35	727.99	782.62	836.57	890.92
	$s, \text{kJ}/(\text{kg K})$			2.502 1	2.720 8	2.891 8	3.042 5	3.181 8	3.313 6

^aAbridged by permission, from *Thermodynamic Properties in SZ* by W. C. Reynolds, Department of Mechanical Engineering, Stanford University.

Table 5 Properties of gaseous hydrogen (PARA)

Pressure, MPa	Property	Value at different temperatures, K							
		100	200	300	400	600	800	1200	1500
0.101 325 (20.28)	$v, m^3/kg$	4.070	8.147	12.22	16.29	24.43	32.57	48.85	61.06
	$h, kJ/kg$	1 399.8	2 971.3	4 509.6	5 976.6	8 880.9	11 806.0	17 833.5	22 547.2
	$s, kJ/(kg K)$	42.689	53.475	59.729	63.952	69.840	74.046	80.146	83.650
0.20 (22.81)	$v, m^3/kg$	2.061	4.130	6.194	8.257	12.38	16.51	24.75	30.94
	$h, kJ/kg$	1 398.3	2 971.3	4 510.1	5 977.3	8 881.7	11 806.9	17 834.3	22 548.0
	$s, kJ/(kg K)$	39.869	50.667	56.924	61.147	67.035	71.242	77.342	80.846
0.50 (27.12)	$v, m^3/kg$	0.824 1	1.656	2.482	3.307	4.957	6.607	9.906	12.38
	$h, kJ/kg$	1 393.6	2 971.5	4 511.6	5 979.4	8 884.2	11 809.5	17 836.9	22 550.6
	$s, kJ/(kg K)$	36.046	46.880	53.143	57.367	63.257	67.463	73.563	77.067
1.0 (31.26)	$v, m^3/kg$	0.4119	0.830 8	1.245	1.658	2.483	3.307	4.957	6.194
	$h, kJ/kg$	1 386.0	2 971.7	4 514.1	5 982.8	8 888.4	11 813.8	17 841.3	22 554.9
	$s, kJ/(kg K)$	33.114	44.008	50.280	54.507	60.398	64.605	70.705	74.209
2.0	$v, m^3/kg$	0.205 9	0.418 4	0.626 1	0.832 8	1.245	1.658	2.482	3.101
	$h, kJ/kg$	1371.4	2 972.3	4 519.1	5 989.7	8 896.7	11 822.6	17 850.1	22 563.5
	$s, kJ/(kg K)$	30.114	41.122	47.413	51.645	57.539	61.747	67.847	71.351
4.0	$v, m^3/kg$	0.103 4	0.212 3	0.316 8	0.420 4	0.626 8	0.832 9	1.245	1.554
	$h, kJ/kg$	1 345.2	2 974.1	4 529.3	6 003.5	8 913.3	11 840.0	17 867.6	22 580.8
	$s, kJ/(kg K)$	26.993	38.213	44.538	48.781	54.681	58.890	64.990	68.494
7.0	$v, m^3/kg$	0.060 19	0.124 0	0.184 3	0.243 6	0.361 6	0.479 3	0.7 14 6	0.891 1
	$h, kJ/kg$	1313.9	2 978.3	4 544.9	6 024.2	8 938.1	11 866.0	17 893.8	22 606.6
	$s, kJ/(kg K)$	24.349	35.834	42.207	46.465	52.374	56.584	62.685	66.188
10	$v, m^3/kg$	0.043 45	0.088 77	0.1312	0.172 9	0.255 6	0.337 9	0.502 5	0.626 0
	$h, kJ/kg$	1 292.9	2 984.2	4 561.0	6 045.1	8 962.9	11 892.0	17 920.0	22 632.3
	$s, kJ/(kg K)$	22.615	34.299	40.715	44.987	50.904	55.116	61.217	64.720
20	$v, m^3/kg$	0.025 28	0.047 95	0.069 45	0.090 43	0.131 8	0.172 9	0.255 1	0.316 7
	$h, kJ/kg$	1281.7	3 015.9	4 617.9	6 115.4	9 045.0	11 978.2	18 007.0	22 718.0
	$s, kJ/(kg K)$	19.291	31.274	37.794	42.105	48.047	52.265	58.367	61.869
50	$v, m^3/kg$	0.015 51	0.024 01	0.032 57	0.040 97	0.057 51	0.073 91	0.106 6	0.131 1
	$h, kJ/kg$	1456.2	3 185.6	4 816.6	6 336.4	9 290.7	12 233.9	18 265.8	22 973.9
	$s, kJ/(kg K)$	15.362	27.268	33.906	38.282	44.275	48.508	54.614	58.113
100	$v, m^3/kg$	0.011 92	0.016 08	0.020 31	0.024 48	0.032 72	0.040 86	0.057 08	0.069 23
	$h, kJ/kg$	1 850.1	3 553.2	5 192.3	6 725.3	9 700.6	12 655.0	18 692.0	23 396.7
	$s, kJ/(kg K)$	12.618	24.3 14	30.983	35.397	41.433	45.682	51.794	55.291

^aAbridged by permission, from *Thermodynamic Properties in SZ* by W. C. Reynolds, Department of Mechanical Engineering, Stanford University.

Table 6 Properties of gaseous mercury^a

Pressure, MPa		Value at different temperatures, K							
		900	1 100	1 200	1 300				
0.20 (670.0)	$v, m^3/kg$	0.186 1	0.206 9	0.227 7	0.248 4	0.269 2	0.289 9	0.310 7	0.331 4
	$h, kJ/kg$	353.51	363.91	374.29	384.68	395.05	405.43	415.80	426.17
	$s, kJ/(kg K)$	0.537 5	0.548 4	0.558 3	0.567 4	0.575 7	0.583 4	0.590 5	0.597 2
0.50 (733.2)	$v, m^3/kg$	0.074 22	0.082 58	0.090 91	0.099 24	0.107 6	0.115 9	0.124 2	0.132 5
	$h, kJ/kg$	353.20	363.65	374.07	384.48	394.89	405.28	415.67	426.06
	$s, kJ/(kg K)$	0.499 3	0.510 3	0.520 2	0.529 3	0.537 6	0.545 3	0.552 5	0.559 2
1.0 (789.7)	$h, v, m^3 kJ/kg/kg$	0.036 35 2.68 92	0.041 363.21 13	0.045 373.70 32	0.049 384.16 5 1	0.053 394.61 68	405.04 0.057 85	415.46 0.062 02	425.87 0.066 18
	$s, kJ/(kg K)$	0.470 2	0.481 3	0.491 3	0.500 4	0.508 7	0.516 5	0.523 7	0.530 4
	$h, v, m^3 kJ/kg/kg$	0.018 351.62 27	0.020 362.32 40	0.022 372.95 53	0.024 383.52 64	0.026 394.05 74	404.55 0.028 84	415.02 0.030 93	425.48 0.033 02
2.0 (855.8)	$s, kJ/(kg K)$	0.440 7	0.452 0	0.462 1	0.471 3	0.479 7	0.487 5	0.494 8	0.501 5

(See footnote on page 5.5.2-5.)

Table 6 Properties of gaseous mercury (Continued)

Pressure, MPa	Property	Value at different temperatures, K							
		900	1000	1100	1200	1300	1400	1500	1600
5.0 (962.8)	$h, \text{J/(kg K)}$		0.007 359.56 96	0.008 370.63 85	0.009 381.54 72	0.010 392.34 58	403.06 0.01143	0.012 413.71 28	424.32 0.013 13
10 (1064)	$s, \text{kJ/(kg K)}$		0.412 2	0.422 8	0.432 3	0.440 9	0.448 9	0.456 2	0.463 0
	$h, \text{J/(kg K)}$			0.004 366.56 28	0.004 378.11 74	0.005 389.40 18	400.5 0.005 1 63	411.48 0.006 06	422.34 0.006 50
	$s, \text{kJ/(kg K)}$			0.391 6	0.401 7	0.410 7	0.418 9	0.426 5	0.433 5

^aAbridged by permission, from *Thermodynamic Properties in SZ* by W. C. Reynolds, Department of Mechanical Engineering, Stanford University.

Table 7 Properties of gaseous nitrogen^a

Pressure, MPa	Property	Value at different temperatures, K							
		200	300	400	500	600	800	1000	1200
0.101 325 (77.35)	$v, \text{m}^3/\text{kg}$	0.584 5	0.878 6	1.172	1.465	1.758	2.344	2.930	3.516
	$h, \text{kJ/kg}$	357.00	461.14	565.30	670.20	776.59	995.91	1224.55	1461.29
	$s, \text{kJ/(kg K)}$	3.982 9	4.405 1	4.704 8	4.938 8	5.132 7	5.447 9	5.702 8	5.918 5
0.50 (93.98)	$v, \text{m}^3/\text{kg}$	0.117 4	0.177 9	0.237 8	0.297 4	0.356 9	0.475 8	0.594 6	0.713 4
	$h, \text{kJ/kg}$	355.05	460.25	564.89	670.03	776.59	996.10	1 224.84	1461.63
	$s, \text{kJ/(kg K)}$	3.501 9	3.928 6	4.229 7	4.464 3	4.658 5	4.973 9	5.228 9	5.444 7
1.0 (103.7)	$v, \text{m}^3/\text{kg}$	0.058 10	0.088 90	0.119 1	0.149 0	0.178 8	0.238 4	0.297 8	0.357 2
	$h, \text{kJ/kg}$	352.58	459.16	564.37	669.84	776.60	996.33	1 225.20	1462.07
	$s, \text{kJ/(kg K)}$	3.287 0	3.719 5	4.022 2	4.257 5	4.452 1	4.767 9	5.023 1	5.238 9
2.0 (115.6)	$v, \text{m}^3/\text{kg}$	0.028 44	0.044 40	0.059 71	0.074 81	0.089 80	0.119 7	0.149 4	0.179 1
	$h, \text{kJ/kg}$	347.60	457.00	563.37	669.47	776.62	996.81	1 225.92	1462.94
	$s, \text{kJ/(kg K)}$	3.062 6	3.507 0	3.813 1	4.049 9	4.245 2	4.561 6	4.817 0	5.033 0
5.0	$v, \text{m}^3/\text{kg}$	0.010 71	0.017 75	0.024 13	0.030 31	0.036 40	0.048 43	0.060 38	0.072 30
	$h, \text{kJ/kg}$	332.45	450.83	560.56	668.48	776.77	998.29	1 228.12	1465.57
	$s, \text{kJ/(kg K)}$	2.733 0	3.215 4	3.5314	3.772 2	3.969 6	4.288 0	4.544 2	4.760 6
10	$v, \text{m}^3/\text{kg}$	0.005 02	0.008 95	0.012 32	0.015 51	0.018 61	0.024 70	0.030 71	0.036 69
	$h, \text{kJ/kg}$	308.56	441.78	556.63	667.31	777.34	1 000.90	1 231.86	1470.01
	$s, \text{kJ/(kg K)}$	2.434 1	2.979 7	3.310 6	3.557 6	3.758 2	4.079 6	4.337 1	4.554 1
20	$v, \text{m}^3/\text{kg}$	0.002 69	0.004 70	0.006 49	0.008 15	0.009 75	0.012 85	0.015 88	0.018 89
	$h, \text{kJ/kg}$	280.28	428.93	551.48	666.60	779.54	1 006.65	1 239.64	1479.06
	$s, \text{kJ/(kg K)}$	2.116 8	2.726 1	3.079 5	3.336 5	3.542 5	3.869 0	4.128 8	4.347 0
40	$v, \text{m}^3/\text{kg}$	0.001 88	0.002 78	0.003 68	0.004 53	0.005 35	0.006 94	0.008 48	0.009 99
	$h, \text{kJ/kg}$	272.71	421.05	550.24	670.61	787.47	1019.85	1 256.13	1497.70
	$s, \text{kJ/(kg K)}$	1.8614	2.466 4	2.838 9	3.107 8	3.320 9	3.655 1	3.918 6	4.138 7
70	$v, \text{m}^3/\text{kg}$	0.001 56	0.002 04	0.002 54	0.003 02	0.003 50	0.004 42	0.005 31	0.006 18
	$h, \text{kJ/kg}$	287.71	431.56	562.23	685.58	805.40	1042.66	1 282.44	1526.54
	$s, \text{kJ/(kg K)}$	1.682 0	2.267 6	2.644 2	2.919 7	3.138 2	3.479 4	3.746 9	3.969 4
100	$v, \text{m}^3/\text{kg}$	0.00142	0.001 75	0.002 09	0.002 43	0.002 76	0.003 41	0.004 04	0.004 66
	$h, \text{kJ/kg}$	309.67	451.53	582.06	706.35	827.54	1 067.65	1 309.89	1555.93
	$s, \text{kJ/(kg K)}$	1.568 9	2.146 1	2.522 2	2.799 7	3.020 8	3.366 2	3.636 3	3.860 6
200	$v, \text{m}^3/\text{kg}$	0.001 21	0.001 38	0.001 55	0.001 72	0.001 89	0.002 22	0.002 54	0.002 86
	$h, \text{kJ/kg}$	393.11	534.36	664.90	790.06	912.85	1 157.26	1404.11	1654.43
	$s, \text{kJ/(kg K)}$	1.337 1	1.911 8	2.287 8	2.567 3	2.791 2	3.142 8	3.418 1	3.646 2

^aAbridged by permission, from *Thermodynamic Properties in SZ* by W. C. Reynolds, Department of Mechanical Engineering, Stanford University.

Table 8 Properties of gaseous oxygen^a

Pressure, MPa	Property	Value at different temperatures, K							
		200	300	400	500	600	700	800	1 000
0.050 (83.94)	$v, \text{m}^3/\text{kg}$	1.038	1.558	2.079	2.598	3.118	3.638	4.158	5.197
	$h, \text{kJ/kg}$	374.65	466.10	559.00	654.63	753.40	855.13	959.43	1 174.09
	$s, \text{kJ}/(\text{kg K})$	4.127 5	4.498 2	4.765 3	4.978 6	5.158 6	5.315 3	5.454 6	5.693 9
0.101 325 (90.19)	$v, \text{m}^3/\text{kg}$	0.511 3	0.768 8	1.026	1.282	1.539	1.795	2.052	2.565
	$h, \text{kJ/kg}$	374.39	465.97	558.94	654.60	753.39	855.14	959.45	1 174.11
	$s, \text{kJ}/(\text{kg K})$	3.943 1	4.314 3	4.581 6	4.795 0	4.975 0	5.131 8	5.271 0	5.510 4
0.20 (97.24)	$v, \text{m}^3/\text{kg}$	0.258 3	0.389 3	0.519 7	0.649 8	0.779 8	0.909 8	1.040	1.300
	$h, \text{kJ/kg}$	373.89	465.73	558.82	654.54	753.38	855.15	959.48	1 174.17
	$s, \text{kJ}/(\text{kg K})$	3.764 7	4.137 0	4.404 7	4.618 1	4.798 2	4.955 1	5.094 4	5.333 7
0.50 (108.8)	$v, \text{m}^3/\text{kg}$	0.102 4	0.155 4	0.207 9	0.260 1	0.312 2	0.364 2	0.416 2	0.520 1
	$h, \text{kJ/kg}$	372.35	464.99	558.44	654.37	753.33	855.19	959.57	1 174.33
	$s, \text{kJ}/(\text{kg K})$	3.521 2	3.896 9	4.165 6	4.379 6	4.559 9	4.716 9	4.856 2	5.095 7
1.0 (119.6)	$v, \text{m}^3/\text{kg}$	0.050 39	0.077 49	0.103 9	0.130 2	0.156 3	0.182 3	0.208 3	0.260 3
	$h, \text{kJ/kg}$	369.73	463.76	557.81	654.09	753.25	855.25	959.73	1 174.59
	$s, \text{kJ}/(\text{kg K})$	3.332 0	3.713 5	3.984 0	4.198 7	4.379 4	4.536 6	4.676 0	4.915 6
2.0 (132.7)	$v, \text{m}^3/\text{kg}$	0.024 39	0.038 53	0.051 98	0.065 20	0.078 32	0.091 37	0.104 4	0.130 4
	$h, \text{kJ/kg}$	364.33	461.29	556.57	653.52	753.11	855.38	960.04	1 175.13
	$s, \text{kJ}/(\text{kg K})$	3.132 8	3.526 6	3.800 7	4.016 9	4.198 4	4.356 0	4.495 8	4.735 6
5.0 (154.4)	$v, \text{m}^3/\text{kg}$	0.008 76	0.015 16	0.020 82	0.026 24	0.031 56	0.036 81	0.042 04	0.052 44
	$h, \text{kJ/kg}$	346.74	453.93	552.90	651.86	752.69	855.78	961.00	1 176.75
	$s, \text{kJ}/(\text{kg K})$	2.831 0	3.268 4	3.553 3	3.774 0	3.957 8	4.116 7	4.257 1	4.497 7
10	$v, \text{m}^3/\text{kg}$	0.003 61	0.007 43	0.010 46	0.013 27	0.015 98	0.018 64	0.021 26	0.026 47
	$h, \text{kJ/kg}$	313.19	442.21	547.14	649.30	752.12	856.53	962.66	1 179.50
	$s, \text{kJ}/(\text{kg K})$	2.523 9	3.055 9	3.358 2	3.586 1	3.773 6	3.934 5	4.076 2	4.318 0
20	$v, \text{m}^3/\text{kg}$	0.001 73	0.003 70	0.005 34	0.006 82	0.008 22	0.009 57	0.010 89	0.013 50
	$h, \text{kJ/kg}$	268.46	422.72	537.55	645.22	751.58	858.40	966.22	1 185.16
	$s, \text{kJ}/(\text{kg K})$	2.183 4	2.820 2	3.151 5	3.391 9	3.585 8	3.750 5	3.894 4	4.138 6

^aAbridged by permission, from *Thermodynamic Properties in SZ* by W. C. Reynolds, Department of Mechanical Engineering, Stanford University.

Table 9 Properties of gaseous propane^a

Pressure, MPa	property	Value at different temperatures, K							
		250	300	350	400	450	500	550	600
0.050 (216.4)	$v, \text{m}^3/\text{kg}$	0.929 1	1.123	1.315	1.505	1.695	1.885	2.074	2.263
	$h, \text{kJ/kg}$	523.67	603.16	693.61	795.32	908.02	1 031.20	1 164.24	1 306.49
	$s, \text{kJ}/(\text{kg K})$	2.410 6	2.699 9	2.978 3	3.249 6	3.514 8	3.774 2	4.027 7	4.275 1
0.101 325 (231.3)	$v, \text{m}^3/\text{kg}$	0.450 9	0.549 4	0.645 5	0.740 4	0.834 7	0.928 6	1.022	1.116
	$h, \text{kJ/kg}$	521.02	601.52	692.49	794.5 1	907.40	1 030.72	1 163.85	1 306.17
	$s, \text{kJ}/(\text{kg K})$	2.269 7	2.562 7	2.842 7	3.114 9	3.380 6	3.640 2	3.893 8	4.1414
0.20 (247.9)	$v, \text{m}^3/\text{kg}$	0.220 8	0.273 6	0.323 8	0.372 8	0.421 1	0.469 1	0.516 9	0.564 5
	$h, \text{kJ/kg}$	515.70	598.29	690.32	792.93	906.21	1 029.78	1 163.09	1 305.54
	$s, \text{kJ}/(\text{kg K})$	2.126 0	2.426 7	2.710 0	2.983 7	3.250 3	3.510 5	3.764 5	4.012 3
0.40 (267.9)	$v, \text{m}^3/\text{kg}$		0.131 8	0.158 6	0.184 0	0.208 8	0.233 2	0.257 4	0.281 4
	$h, \text{kJ/kg}$		591.44	685.79	789.70	903.77	1 027.87	1 161.55	1 304.27
	$s, \text{kJ}/(\text{kg K})$		2.279 4	2.570 0	2.847 2	3.115 7	3.377 0	3.631 7	3.879 9
1.0 (300.3)	$v, \text{m}^3/\text{kg}$			0.059 15	0.070 65	0.081 35	0.091 63	0.101 7	0.111 6
	$h, \text{kJ/kg}$			671.19	779.59	896.28	1 022.05	1 156.89	1 300.45
	$s, \text{kJ}/(\text{kg K})$			2.366 9	2.656 2	2.930 8	3.195 7	3.452 6	3.702 3
2.0 (330.4)	$v, \text{m}^3/\text{kg}$			0.025 34	0.032 68	0.038 82	0.044 44	0.049 79	0.054 97
	$h, \text{kJ/kg}$			641.60	761.13	883.12	1 012.06	1 148.99	1 294.01
	$s, \text{kJ}/(\text{kg K})$			2.172 3	2.491 6	2.778 8	3.050 4	3.311 3	3.563 5

(See footnote on page 5.5.2-7.)

Table 9 Properties of gaseous propane (Continued)

Pressure, MPa	Property	Value at different temperatures, K							
		250	300	350	400	450	500	550	600
4.0 (366.5)	v , m ³ /kg				0.013 16	0.017 45	0.020 85	0.023 89	0.026 73
	h , kJ/kg				714.17	853.84	990.91	1 132.70	1 280.98
	s , kJ/(kg K)				2.270 2	2.599 4	2.888 2	3.158 4	3.416 4
7.0	v , m ³ /kg				0.004 18	0.008 22	0.010 80	0.012 88	0.014 73
	h , kJ/kg				591.69	800.86	956.60	1 107.49	1261.33
	s , kJ/(kg K)				1.906 4	2.401 9	2.730 3	3.017 9	3.285 6
10	v , m ³ /kg				0.002 98	0.004 95	0.006 97	0.008 62	0.010 05
	h , kJ/kg				544.14	746.96	921.77	1082.57	1 242.27
	s , kJ/(kg K)				1.761 9	2.240 0	2.608 8	2.915 4	3.193 3
20	v , m ³ /kg				0.002 38	0.002 87	0.003 55	0.004 31	0.005 06
	h , kJ/kg				517.85	678.83	849.71	1021.44	1 192.46
	s , kJ/(kg K)				1.6314	2.009 8	2.370 2	2.697 6	2.995 2

^aAbridged by permission, from *Thermodynamic Properties in SZ* by W. C. Reynolds, Department of Mechanical Engineering, Stanford University.

Table 10 Properties of gaseous propylene^a

Pressure, MPa	Property	Value at different temperatures, K							
		260	300	340	380	420	460	500	540
0.070 (217.6)	v , m ³ /kg	0.722 9	0.838 5	0.953 3	1.068	1.181	1.295	1.409	1.522
	h , kJ/kg	545.62	604.29	668.72	738.90	815.18	897.33	985.06	1078.00
	s , kJ/(kg K)	2.492 4	2.702 1	2.903 2	3.098 4	3.289 2	3.475 9	3.658 7	3.837 5
0.101 325 (225.4)	v , m ³ /kg	0.496 0	0.576 7	0.656 6	0.735 9	0.815 0	0.893 7	0.972 4	1.051
	h , kJ/kg	544.60	603.51	668.01	738.40	814.77	896.98	984.75	1 077.73
	s , kJ/(kg K)	2.416 7	2.627 3	2.828 9	3.024 5	3.215 4	3.402 3	3.585 2	3.764 0
0.20 (241.6)	v , m ³ /kg	0.245 6	0.288 0	0.329 5	0.370 3	0.410 9	0.451 2	0.491 3	0.531 4
	h , kJ/kg	541.28	601.00	666.04	736.81	813.45	895.87	983.80	1 076.91
	s , kJ/(kg K)	2.273 8	2.487 3	2.690 6	2.887 2	3.078 9	3.266 2	3.449 5	3.628 5
0.40 (261.0)	v , m ³ /kg		0.139 6	0.161 4	0.182 6	0.203 4	0.224 0	0.244 4	0.264 6
	h , kJ/kg		595.69	661.96	733.55	810.77	893.61	981.87	1 075.23
	s , kJ/(kg K)		2.338 3	2.545 4	2.744 4	2.937 5	3.125 8	3.309 7	3.489 3
0.70 (279.3)	v , m ³ /kg		0.075 76	0.089 33	0.102 1	0.114 5	0.126 6	0.138 5	0.150 3
	h , kJ/kg		587.03	655.54	728.51	806.67	890.19	978.96	1072.72
	s , kJ/(kg K)		2.207 5	2.421 8	2.624 6	2.820 0	3.009 9	3.194 9	3.375 2
1.0 (292.5)	v , m ³ /kg		0.049 91	0.060 39	0.069 89	0.078 91	0.087 64	0.096 19	0.104 6
	h , kJ/kg		577.25	648.73	723.31	802.50	886.73	976.03	1 070.20
	s , kJ/(kg K)		2.113 6	2.337 2	2.544 5	2.742 5	2.934 0	3.120 1	3.301 2
2.0 (321.9)	v , m ³ /kg			0.026 08	0.032 12	0.037 34	0.042 19	0.046 81	0.051 29
	h , kJ/kg			621.71	704.43	787.93	874.92	966.15	1061.76
	s , kJ/(kg K)			2.141 7	2.371 8	2.580 7	2.778 4	2.968 6	3.152 5
4.0 (357.1)	v , m ³ /kg				0.012 56	0.016 41	0.019 44	0.022 15	0.024 67
	h , kJ/kg				654.01	754.88	849.80	945.84	1 044.76
	s , kJ/(kg K)				2.132 5	2.385 2	2.601 1	2.801 3	2.991 5
7.0	v , m ³ /kg				0.003 14	0.007 16	0.009 70	0.011 64	0.013 34
	h , kJ/kg				490.13	689.17	807.70	914.06	1019.08
	s , kJ/(kg K)				1.649 8	2.150 4	2.420 5	2.642 2	2.844 3
10	v , m ³ /kg				1.002 63	0.003 99	0.005 96	0.007 56	0.008 91
	h , kJ/kg				463.63	618.60	762.41	881.75	993.83
	s , kJ/(kg K)				1.557 8	1.944 9	2.272 6	2.521 6	2.737 2

^aAbridged by permission, from *Thermodynamic Properties in SZ* by W. C. Reynolds, Department of Mechanical Engineering, Stanford University.

Table 11 Properties of gaseous air^a

Pressure, MPa	Property	Value at different temperatures, K								
		200	300	400	500	600	700	800	900	1000
0.050 (76.24)	$v, m^3/kg$	1.147	1.722	2.297	2.871	3.445	4.020	4.594	5.168	5.742
	$h, kJ/kg$	359.56	459.96	560.79	662.81	766.71	872.87	981.41	1 092.23	1205.16
	$s, kJ/(kg K)$	4.329 8	4.736 8	5.026 9	5.254 4	5.443 8	5.607 4	5.752 3	5.882 8	6.001 8
	$u, kJ/kg$	302.22	373.86	445.95	519.25	594.44	671.89	751.72	833.83	918.04
0.101 325 (81.82)	$v, m^3/kg$	0.565 3	0.849 7	1.133	1.417	1.701	1.984	2.267	2.551	2.834
	$h, kJ/kg$	359.31	459.85	560.73	662.79	766.70	872.88	981.43	1 092.26	1 205.19
	$s, kJ/(kg K)$	4.126 1	4.533 7	4.823 9	5.0516	5.241 0	5.404 6	5.549 5	5.680 0	5.799 0
	$u, kJ/kg$	302.03	373.75	445.88	5 19.20	594.40	671.86	751.69	833.81	918.03
0.20 (88.14)	$v, m^3/kg$	0.285 7	0.430 4	0.574 4	0.718 2	0.861 9	1.006	1.149	1.293	1.436
	$h, kJ/kg$	358.83	459.63	560.62	662.74	766.70	872.90	981.47	1 092.31	1 205.25
	$s, kJ/(kg K)$	3.929 1	4.337 9	4.628 4	4.856 2	5.045 7	5.209 3	5.354 3	5.484 8	5.603 8
	$u, kJ/kg$	301.68	373.55	445.75	519.11	594.32	671.80	751.65	833.77	918.00
0.40 (95.78)	$v, m^3/kg$	0.142 2	0.215 1	0.287 3	0.359 3	0.431 3	0.503 1	0.575 0	0.646 8	0.718 6
	$h, kJ/kg$	357.85	459.18	560.40	662.64	766.68	872.94	981.54	1092.41	1 205.37
	$s, kJ/(kg K)$	3.726 6	4.137 5	4.428 7	4.656 8	4.846 4	5.010 2	5.155 2	5.285 7	5.404 7
	$u, kJ/kg$	300.97	373.15	445.48	518.91	594.17	671.68	751.55	833.70	917.94
0.70 (103.0)	$v, m^3/kg$	0.080 69	0.122 8	0.164 3	0.205 6	0.246 7	0.287 8	0.328 9	0.370 0	0.411 0
	$h, kJ/kg$	356.37	458.50	560.07	662.50	766.65	872.99	981.65	1 092.56	1 205.55
	$s, kJ/(kg K)$	3.560 6	3.974 9	4.267 1	4.495 6	4.685 4	4.849 3	4.994 3	5.125 0	5.244 0
	$u, kJ/kg$	299.89	372.54	445.07	518.61	593.95	671.51	751.41	833.58	917.84
1.0 (108.2)	$v, m^3/kg$	0.056 09	0.085 PO	0.115 1	0.144 0	0.172 9	0.201 7	0.230 5	0.259 2	0.288 0
	$h, kJ/kg$	354.89	457.83	559.74	662.36	766.63	873.04	981.76	1092.72	1 205.74
	$s, kJ/(kg K)$	3.452 7	3.870 5	4.163 7	4.392 6	4.582 6	4.746 6	4.891 8	5.022 4	5.141 5
	$u, kJ/kg$	298.80	371.94	444.66	518.32	593.72	671.33	751.27	833.47	917.75
2.0 (119.8)	$v, m^3/kg$	0.027 39	0.042 85	0.057 67	0.072 28	0.086 79	0.101 2	0.115 7	0.130 1	0.144 5
	$h, kJ/kg$	349.87	455.63	558.67	661.90	766.56	873.23	982.14	1 093.23	1 206.36
	$s, kJ/(kg K)$	3.235 3	3.664 9	3.9614	4.191 7	4.382 4	4.546 8	4.692 2	4.823 0	4.942 2
	$u, kJ/kg$	295.09	369.92	443.32	517.34	592.98	670.75	750.81	833.10	917.45
5.0	$v, m^3/kg$	0.010 22	0.017 07	0.023 26	0.029 24	0.035 13	0.040 97	0.046 77	0.052 56	0.058 34
	$h, kJ/kg$	334.39	449.26	555.63	660.66	766.43	873.86	983.31	1 094.80	1 208.24
	$s, kJ/(kg K)$	2.914 2	3.382 4	3.688 7	3.923 0	4.115 8	4.281 4	4.427 5	4.558 8	4.678 3
	$u, kJ/kg$	283.27	363.91	439.34	5 14.46	590.79	669.04	749.44	832.00	916.55
7.0	$v, m^3/kg$	0.007 01	0.012 19	0.016 72	0.021 05	0.025 29	0.029 49	0.033 65	0.037 80	0.041 94
	$h, kJ/kg$	323.93	445.27	553.77	659.93	766.41	874.33	984.12	1 095.88	1 209.51
	$s, kJ/(kg K)$	2.777 6	3.273 4	3.585 9	3.822 8	4.016 9	4.183 2	4.329 8	4.461 4	4.581 1
	$u, kJ/kg$	274.89	359.96	436.75	512.58	589.36	667.91	748.55	831.27	915.96
10	$v, m^3/kg$	0.004 68	0.008 55	0.011 83	0.014 92	0.017 92	0.020 88	0.023 82	0.026 73	0.029 64
	$h, kJ/kg$	308.87	439.71	551.23	659.00	766.50	875.11	985.40	1097.53	1211.45
	$s, kJ/(kg K)$	2.616 9	3.153 4	3.474 7	3.715 2	3.911 2	4.078 6	4.225 8	4.357 9	4.477 9
	$u, kJ/kg$	262.09	354.16	432.96	509.82	587.26	666.26	747.22	830.20	915.09
20	$v, m^3/kg$	0.002 44	0.004 44	0.006 18	0.007 80	0.009 35	0.010 86	0.012 35	0.013 83	0.015 29
	$h, kJ/kg$	277.13	425.39	544.95	657.23	767.64	878.29	990.07	1 103.34	1 218.14
	$s, kJ/(kg K)$	2.296 7	2.905 3	3.250 1	3.500 8	3.702 1	3.872 7	4.021 9	4.155 3	4.276 3
	$u, kJ/kg$	228.33	336.54	421.27	501.25	580.66	661.04	743.02	826.78	912.29
50	$v, m^3/kg$	0.001 59	0.002 26	0.002 95	0.003 62	0.004 26	0.004 89	0.005 50	0.006 10	0.006 70
	$h, kJ/kg$	269.73	414.72	542.54	661.80	777.54	892.28	1 007.28	1 123.10	1 239.97
	$s, kJ/(kg K)$	1.979 7	2.570 6	2.939 2	3.205 5	3.416 6	3.593 5	3.747 0	3.883 4	4.006 5
	$u, kJ/kg$	190.47	301.91	395.05	480.91	564.45	647.89	732.23	817.86	904.89
70	$v, m^3/kg$	0.001 43	0.001 89	0.002 37	0.002 85	0.003 31	0.003 76	0.004 20	0.004 64	0.005 07
	$h, kJ/kg$	279.48	421.23	549.50	670.41	787.92	904.27	1 020.66	1137.61	1 255.56
	$s, kJ/(kg K)$	1.878 4	2.455 4	2.825 2	3.095 2	3.309 5	3.488 8	3.644 2	3.782 1	3.906 2
	$u, kJ/kg$	179.21	288.78	383.32	471.01	556.16	640.94	726.38	812.93	900.73

(See footnote on page 5.5.2-9.)

Table 11 Properties of gaseous air (Continued)

Pressure, MPa	Property	Value at different temperatures, K								
		200	300	400	500	600	700	800	900	1000
100	$v, \text{m}^3/\text{kg}$	0.001 31	0.001 62	0.00195	0.002 28	0.002 60	0.002 92	0.003 23	0.003 54	0.003 84
	$h, \text{kJ/kg}$	298.89	438.15	566.11	687.97	806.89	924.73	1 042.54	1 160.85	1 279.90
	$s, \text{kJ}/(\text{kg K})$	1.7710	2.337 7	2.706 4	2.978 5	3.195 3	3.377 0	3.534 3	3.673 6	3.799 1
	$u, \text{kJ/kg}$	168.38	275.91	370.94	459.94	546.51	632.61	719.21	806.78	895.47
200	$v, \text{m}^3/\text{kg}$	0.001 12	0.001 28	0.001 45	0.001 61	0.001 77	0.001 93	0.002 09	0.002 25	0.002 40
	$h, \text{kJ/kg}$	374.30	512.21	639.81	762.39	882.84	1 002.71	1 122.77	1 243.39	1 364.71
	$s, \text{kJ}/(\text{kg K})$	1.550 7	2.111 8	2.479 4	2.753 0	2.972 7	3.157 5	3.317 8	3.459 8	3.587 6
	$u, \text{kJ/kg}$	151.20	255.87	350.61	440.54	528.59	616.37	704.70	793.94	884.22

^aAbridged by permission, from *Thermodynamic Properties in SI* by W. C. Reynolds, Department of Mechanical Engineering, Stanford University.

Table 12 Properties of gaseous water^a

Pressure, MPa	Property	Value at different temperatures, K							
		400	450	500	550	600	650	700	750
0.070 (363.1)	$v, \text{m}^3/\text{kg}$	2.617	2.953	3.287	3.619	3.950	4.281	4.612	4.942
	$h, \text{kJ/kg}$	2 732.7	2 830.8	2 929.1	3 028.3	3 128.7	3 230.5	3 333.8	3 438.8
	$s, \text{kJ}/(\text{kg K})$	7.670 7	7.901 9	8.109 0	8.298 0	8.472 7	8.635 7	8.788 9	8.933 7
	$u, \text{kJ/kg}$	2 549.5	2 624.1	2 699.0	2 774.9	2 852.1	2 930.8	3 011.0	3 092.9
0.101325 (373.1)	$v, \text{m}^3/\text{kg}$	1.802	2.036	2.268	2.498	2.727	2.956	3.185	3.413
	$h, \text{kJ/kg}$	2 729.7	2 829.0	2 927.9	3 027.4	3 128.0	3 229.9	3 333.4	3 438.4
	$s, \text{kJ}/(\text{kg K})$	7.494 2	7.728 1	7.936 5	8.126 1	8.301 2	8.464 4	8.617 7	8.762 7
	$u, \text{kJ/kg}$	2 547.2	2 622.7	2 698.1	2 774.3	2 851.6	2 930.4	3 010.7	3 092.6
1.0 (453.1)	$v, \text{m}^3/\text{kg}$			0.220 6	0.246 4	0.271 2	0.295 5	0.319 4	0.343 2
	$h, \text{kJ/kg}$			2 890.2	3 000.9	3 108.0	3 214.2	3 320.7	3 428.0
	$s, \text{kJ}/(\text{kg K})$			6.822 3	7.033 3	7.219 8	7.389 8	7.547 6	7.695 6
	$u, \text{kJ/kg}$			2 669.6	2 754.5	2 836.8	2 918.8	3 001.3	3 084.8

		Value at different temperatures, K						
		800	850	900	950	1000	1 100	1 200
0.070 (363.1)	$v, \text{m}^3/\text{kg}$	5.272	5.602	5.932	6.262	6.592	7.251	7.911
	$h, \text{kJ/kg}$	3 545.4	3 653.8	3 763.8	3 875.6	3 989.1	4 221.5	4 460.7
	$s, \text{kJ}/(\text{kg K})$	9.071 3	9.202 7	9.328 4	9.449 3	9.565 8	9.787 2	9.995 3
	$u, \text{kJ/kg}$	3 176.4	3 261.6	3 348.6	3 437.3	3 527.7	3 713.9	3 906.9
0.101 325 (373.1)	$v, \text{m}^3/\text{kg}$	3.641	3.870	4.098	4.326	4.554	5.009	5.465
	$h, \text{kJ/kg}$	3 545.1	3 653.5	3 763.6	3 875.4	3 989.0	4 221.3	4 460.6
	$s, \text{kJ}/(\text{kg K})$	8.900 4	9.031 7	9.157 6	9.278 5	9.395 0	9.616 4	9.824 5
	$u, \text{kJ/kg}$	3 176.2	3 261.4	3 348.4	3 437.1	3 527.6	3 713.8	3 906.8
1.0 (453.1)	$v, \text{m}^3/\text{kg}$	0.366 8	0.390 2	0.413 7	0.437 0	0.460 3	0.506 8	0.553 2
	$h, \text{kJ/kg}$	3 536.4	3 646.1	3 757.3	3 870.0	3 984.3	4 217.6	4 457.6
	$s, \text{kJ}/(\text{kg K})$	7.835 6	7.968 6	8.095 7	8.217 5	8.334 8	8.557 1	8.765 9
	$u, \text{kJ/kg}$	3 169.6	3 255.9	3 343.6	3 433.0	3 524.0	3 710.8	3 904.4

		Value at different temperatures, K						
		600	650	700	750	800	900	1000
3.0 (507.1).	$v, \text{m}^3/\text{kg}$	0.086 28	0.095 32	0.104 0	0.112 4	0.120 6	0.136 7	0.152 6
	$h, \text{kJ/kg}$	3 059.6	3 177.3	3 291.3	3 404.0	3 516.5	3 743.1	3 973.7
	$s, \text{kJ}/(\text{kg K})$	6.651 6	6.840 2	7.009 1	7.164 6	7.309 8	7.576 7	7.819 6
	$u, \text{kJ/kg}$	2 800.7	2 891.4	2 979.4	3 066.9	3 154.7	3 332.8	3 515.8

(See footnote on page 5.5.2-10.)

Table 12 Properties of gaseous water (Continued)

		Value at different temperatures, K								
Pressure, MPa	Property	600	650	700	750	800	900	1000	1 100	
4.0 (5 23.6)	$v, \text{m}^3/\text{kg}$	0.063 04	0.070 24	0.076 99	0.083 49	0.089 81	0.102 1	0.114 2	0.126 1	
	$h, \text{kJ/kg}$	3 033.0	3 157.8	3 276.1	3 391.6	3 506.3	3 735.8	3 968.3	4 205.3	
	$s, \text{kJ/(kg K)}$	6.484 7	6.684 6	6.860 0	7.019 4	7.167 4	7.437 8	7.682 7	7.908 5	
	$u, \text{kJ/kg}$	2 780.8	2 876.8	2 968.1	3 057.7	3 147.0	3 327.4	3 511.7	3 701.1	
6.0 (548.8)	$v, \text{m}^3/\text{kg}$	0.039 58	0.045 07	0.049 98	0.054 59	0.059 01	0.067 50	0.075 71	0.083 75	
	$h, \text{kJ/kg}$	2 973.8	3 116.3	3 244.4	3 366.3	3 485.5	3 721.2	3 957.5	4 197.0	
	$s, \text{kJ/(kg K)}$	6.220 1	6.448 6	6.638 5	6.806 7	6.960 5	7.238 2	7.487 2	7.715 4	
	$u, \text{kJ/kg}$	2 736.3	2 845.9	2 944.5	3 038.8	3 131.4	3 316.2	3 503.3	3 694.5	
8.0 (568.2)	$v, \text{m}^3/\text{kg}$	0.027 59	0.032 39	0.036 43	0.040 11	0.043 59	0.050 18	0.056 48	0.062 60	
	$h, \text{kJ/kg}$	2 904.1	3 071.1	3 210.9	3 340.0	3 464.0	3 706.2	3 946.6	4 188.7	
	$s, \text{kJ/(kg K)}$	5.993 8	6.261 7	6.469 1	6.647 2	6.807 3	7.092 7	7.345 9	7.576 6	
	$u, \text{kJ/kg}$	2 683.3	2 812.1	2 919.5	3 019.1	3 115.3	3 304.8	3 494.8	3 687.8	
10 (584.2)	$v, \text{m}^3/\text{kg}$	0.020 08	0.024 68	0.028 25	0.031 41	0.034 34	0.039 79	0.044 94	0.049 92	
	$h, \text{kJ/kg}$	2 818.3	3 021.4	3 175.6	3 312.6	3 442.0	3 691.0	3 935.6	4 180.3	
	$s, \text{kJ/(kg K)}$	5.772 2	6.098 3	6.327 0	6.516 2	6.683 3	6.976 7	7.234 4	7.467 6	
	$u, \text{kJ/kg}$	2 617.5	2 774.6	2 893.1	2 998.5	3 098.7	3 293.1	3 486.2	3 681.2	
15 (615.4)	$v, \text{m}^3/\text{kg}$		0.014 04	0.017 23	0.019 75	0.021 96	0.025 93	0.029 56	0.033 01	
	$h, \text{kJ/kg}$		2 868.5	3 077.4	3 239.6	3 384.3	3 652.0	3 907.7	4 159.4	
	$s, \text{kJ/(kg K)}$		5.719 2	6.029 5	6.253 6	6.440 4	6.755 9	7.025 4	7.265 3	
	$u, \text{kJ/kg}$		2 658.0	2 818.9	2 943.5	3 054.9	3 263.0	3 464.3	3 664.3	
20 (639.0)	$v, \text{m}^3/\text{kg}$		0.007 90	0.011 56	0.013 86	0.015 75	0.019 00	0.021 88	0.024 56	
	$h, \text{kJ/kg}$		2 625.1	2 961.0	3 159.4	3 323.0	3 611.7	3 879.3	4 138.5	
	$s, \text{kJ/(kg K)}$		5.2616	5.762 2	6.036 3	6.247 7	6.588 1	6.870 2	7.117 2	
	$u, \text{kJ/kg}$		2 467.1	2 729.9	2 882.2	3 007.9	3 231.6	3 441.8	3 647.3	
Value at different temperatures, K										
		700	750	800	850	900	950	1000	1 050	1 100
30	$v, \text{m}^3/\text{kg}$	0.005 43	0.007 86	0.009 5 1	0.010 87	0.012 08	0.013 18	0.014 21	0.015 18	0.016 12
	$h, \text{kJ/kg}$	2 633.2	2 973.5	3 189.4	3 367.6	3 528.0	3 678.1	3 821.6	3 960.6	4 096.5
	$s, \text{kJ/(kg K)}$	5.177 6	5.649 0	5.928 0	6.144 2	6.327 6	6.490 0	6.637 3	6.772 9	6.899 3
	$u, \text{kJ/kg}$	2 470.4	2 737.6	2 904.0	3 041.4	3 165.7	3 282.8	3 395.4	3 505.1	3 612.8
40	$v, \text{m}^3/\text{kg}$	0.002 60	0.004 83	0.006 40	0.007 60	0.008 63	0.009 54	0.010 39	0.011 17	0.011 92
	$h, \text{kJ/kg}$	2 221.6	2 752.8	3 043.7	3 258.4	3 441.6	3 607.8	3 763.3	3 911.6	4 054.6
	$s, \text{kJ/(kg K)}$	4.536 3	5.272 0	5.648 3	5.908 9	6.118 5	6.298 2	6.457 8	6.602 5	6.735 7
	$u, \text{kJ/kg}$	2 117.4	2 559.5	2 787.8	2 954.3	3 096.4	3 226.0	3 347.9	3 464.7	3 577.8
50	$v, \text{m}^3/\text{kg}$	0.002 03	0.003 23	0.004 59	0.005 67	0.006 58	0.007 38	0.008 11	0.008 78	0.009 41
	$h, \text{kJ/kg}$	2 074.8	2 535.1	2 893.2	3 147.2	3 354.5	3 537.3	3 705.1	3 862.8	4 013.2
	$s, \text{kJ/(kg K)}$	4.294 3	4.929 3	5.392 6	5.700 9	5.938 0	6.135 8	6.308 0	6.461 9	6.601 9
	$u, \text{kJ/kg}$	1973.0	2 373.7	2 663.9	2 863.5	3 025.2	3 168.1	3 299.6	3 423.8	3 542.6
60	$v, \text{m}^3/\text{kg}$	0.001 83	0.002 51	0.003 50	0.004 44	0.005 26	0.005 97	0.006 61	0.007 20	0.007 75
	$h, \text{kJ/kg}$	2 013.6	2 387.9	2 754.9	3 039.5	3 269.1	3 468.0	3 647.8	3 814.7	3 972.3
	$s, \text{kJ/(kg K)}$	4.179 5	4.695 4	5.169 7	5.515 2	5.777 9	5.993 0	6.177 6	6.340 5	6.487 2
	$u, \text{kJ/kg}$	1903.6	2 237.5	2 544.7	2 772.8	2 953.8	3 109.9	3 251.2	3 382.7	3 507.3
70	$v, \text{m}^3/\text{kg}$	0.001 72	0.002 17	0.002 87	0.003 64	0.004 35	0.004 98	0.005 56	0.006 09	0.006 58
	$h, \text{kJ/kg}$	1977.8	2 301.9	2 644.3	2 941.8	3 188.5	3 401.4	3 592.2	3 767.9	3 932.5
	$s, \text{kJ/(kg K)}$	4.103 1	4.549 8	4.992 0	5.353 0	5.635 3	5.865 6	6.061 5	6.232 9	6.386 1
	$u, \text{kJ/kg}$	1 857.6	2 150.3	2 443.7	2 687.2	2 884.2	3 052.6	3 203.2	3 341.9	3 472.0
80	$v, \text{m}^3/\text{kg}$	0.001 64	0.001 97	0.002 48	0.003 10	0.003 7 1	0.004 27	0.004 79	0.005 27	0.005 71
	$h, \text{kJ/kg}$	1 953.8	2 248.4	2 563.0	2 858.7	3 115.3	3 339.0	3 539.4	3 722.9	3 893.9
	$s, \text{kJ/(kg K)}$	4.044 8	4.451 0	4.857 1	5.215 9	5.509 4	5.7514	5.957 1	6.136 2	6.295 3
	$u, \text{kJ/kg}$	1 822.6	2 090.5	2 364.3	2 610.8	2 818.6	2 997.2	3 156.1	3 301.5	3 436.9

(See footnote on page 5.5.2-11.)

Table 12 Properties of gaseous water (*Continued*)

Pressure, MPa	Property	Value at different temperatures, K								
		700	750	800	850	900	950	1000	1050	1 100
100	$v, \text{m}^3/\text{kg}$	0.001 53	0.001 76	0.002 07	0.002 47	0.002 91	0.003 35	0.003 77	0.004 16	0.004 53
	$h, \text{kJ/kg}$	1923.7	2 186.1	2 461.2	2 736.7	2 995.5	3 230.7	3 444.2	3 640.0	3 821.8
	$s, \text{kJ}/(\text{kg K})$	3.956 7	4.318 6	4.673 5	5.007 7	5.303 7	5.558 1	5.777 2	5.968 4	6.137 5
	$u, \text{kJ/kg}$	1 770.5	2 010.4	2 254.1	2 489.8	2 704.5	2 895.7	3 067.3	3 223.7	3 368.4

^aAbridged by permission, from *Thermodynamic Properties in SI* by W. C. Reynolds, Department of Mechanical Engineering, Stanford University.

REFERENCE TO SECTION 5.5.2

1. Reynolds, W. C., *Thermodynamic Properties in SI*, Department of Mechanical Engineering, Stanford University, Stanford, California **94305**, 1979.

5.5.3

Properties of liquid water

K. Schwier

■ Critical properties: $p_c = 221.20$ bar; $T_c = 374.15^\circ\text{C}$; $T_c = 647.30$ K; $\rho_c = 315$ kg/m³; Molecular weight: $\tilde{M} = 18.016$ kg/kmol.

Table 1 Properties of liquid water at $p = 1$ bar^a

T , °C	ρ , kg/m ³	c_p , kJ/kg K	β , 10 ⁻³ /K	λ , 10 ⁻³ W/m K	η , 10 ⁻⁶ kg/m s	ν , 10 ⁻⁶ m ² /s	κ , 10 ⁻⁶ m ² /s	Pr
0	999.8	4.217	-0.085 2	569	1 750	1.75	0.135	13.0
10	999.8	4.192	+ 0.082 3	587	1300	1.30	0.140	9.28
20	998.4	4.182	0.206 7	604	1 000	1.00	0.144	6.94
30	995.8	4.178	0.305 6	618	797	0.800	0.148	5.39
40	992.3	4.179	0.389 0	632	651	0.656	0.153	4.30
50	988.1	4.181	0.462 3	643	544	0.551	0.156	3.54
60	983.2	4.185	0.528 8	654	463	0.471	0.159	2.96
70	977.7	4.190	0.590 0	662	400	0.409	0.162	2.53
80	971.6	4.196	0.647 3	670	351	0.361	0.164	2.20
90	965.2	4.205	0.701 8	676	311	0.322	0.166	1.94

^a T , Temperature, C; ρ , density; c_p , specific heat capacity; β , thermal expansion coefficient; λ , thermal conductivity; η , dynamic viscosity; ν , kinematic viscosity; κ , thermal diffusivity; Pr, Prandtl number.

Reprinted from *VDI-Wärmeatlas*, 2d ed., Düsseldorf, Verein Deutscher Ingenieure, 1974.

Table 2 Density ρ of liquid water as a function of pressure and temperature^a

Pressure, bar	Temperature, °C								
	0	20	50	100	150	200	250	300	350
1	999.9	998.4	988.1						
5	1 000.1	998.6	988.3	958.4	916.8				
10	1 000.2	998.8	988.5	958.6	917.1				
20	1 000.7	999.2	988.9	959.0	917.7	865.0			
30	1001.2	999.8	989.4	959.6	918.3	865.8			
40	1 001.7	1 000.1	989.8	960.0	918.8	866.6	799.2		
50	1 002.2	1 000.5	990.2	960.5	919.4	867.3	800.4		
60	1 002.7	1 001.0	990.7	961.0	920.0	868.1	801.6		
70	1003.2	1001.4	991.1	961.4	920.5	868.9	802.7		
80	1 003.7	1 001.9	991.5	961.9	921.1	869.6	803.8		
90	1004.2	1 002.3	991.9	962.4	921.7	870.4	804.9	713.1	
100	1004.7	1 002.8	992.4	962.8	922.2	871.1	806.0	715.4	
150	1 007.2	1 005.0	994.5	965.1	925.0	874.7	811.4	725.8	
200	1 009.6	1 007.2	996.6	967.5	927.7	878.2	816.5	735.0	600.3
250	1 012.1	1 009.3	998.7	969.7	930.4	881.6	821.3	743.4	624.9
300	1 014.5	1011.5	1 000.7	971.9	933.0	884.9	826.0	751.0	643.4
350	1 016.9	1013.6	1 002.7	974.1	935.6	888.1	830.4	758.1	658.5
400	1019.2	1015.8	1004.7	976.2	938.1	891.3	834.7	764.7	671.4
450	1 021.5	1017.9	1 006.7	978.3	940.5	894.3	838.8	771.0	682.7
500	1 023.8	1019.9	1 008.7	980.5	943.0	897.3	842.8	776.9	692.9
600	1 028.4	1 024.0	1 012.6	984.5	947.7	903.1	850.3	787.7	710.7
700	1 032.9	1 028.1	1 016.4	988.5	952.3	908.6	857.5	797.5	725.9
800	1 037.2	1032.1	1 020.1	992.4	956.7	914.0	864.2	806.7	739.3
900	1041.4	1 036.0	1 023.8	996.3	961.1	919.2	870.6	815.2	751.5
1 000	1 045.5	1 039.9	1 027.4	1 000.0	965.3	924.2	876.7	823.2	762.5

^a ρ in kg/m³.**Table 3 Constant pressure specific heat c_p of liquid water as a function of pressure^a and temperature**

Pressure, bar	Temperature, °C								
	0	20	50	100	150	200	250	300	350
1	4.217	4.182	4.181						
5	4.215	4.181	4.180	4.215	4.310				
10	4.212	4.179	4.179	4.214	4.308				
50	4.191	4.166	4.170	4.205	4.296	4.477	4.855	3.299	
100	4.165	4.151	4.158	4.194	4.281	4.450	4.791	5.703	4.042
150	4.141	4.137	4.148	4.183	4.266	4.425	4.735	5.495	8.863
200	4.117	4.123	4.137	4.173	4.252	4.402	4.685	5.332	8.103
250	4.095	4.109	4.127	4.163	4.239	4.379	4.639	5.201	7.017
300	4.073	4.097	4.117	4.153	4.226	4.358	4.598	5.091	6.451
350	4.052	4.084	4.107	4.144	4.214	4.338	4.560	4.999	6.084
400	4.032	4.073	4.098	4.135	4.202	4.319	4.525	4.919	5.820
450	4.013	4.062	4.089	4.126	4.190	4.301	4.493	4.848	5.616
500	3.994	4.051	4.081	4.117	4.179	4.284	4.463	4.786	5.451
600	3.957	4.032	4.064	4.100	4.157	4.252	4.410	4.681	5.200
700	3.920	4.014	4.049	4.084	4.137	4.222	4.362	4.595	5.014
800	3.883	3.997	4.035	4.068	4.117	4.195	4.320	4.523	4.871
900	3.844	3.982	4.022	4.054	4.099	4.169	4.282	4.462	4.757
1000	3.800	3.968	4.010	4.039	4.081	4.145	4.248	4.410	4.663

^a c_p in kJ/kg K.

Table 4 Thermal expansion coefficient $\beta = (1/v)(\partial v/\partial T)_p$ of liquid water as a function of pressure and temperature'

Pressure, bar	Temperature, °C								
	0	20	50	100	150	200	250	300	350
1	-0.085 2	0.206 7	0.462 3						
5	-0.083 8	0.207 2	0.462 2	0.753 9	1.024				
10	-0.082 0	0.207 9	0.462 0	0.753 0	1.022				
50	-0.067 8	0.213 3	0.460 5	0.745 5	1.007	1.347	1.936		
100	-0.049 9	0.220 1	0.458 9	0.736 6	0.990 2	1.312	1.848	3.189	
150	-0.032 0	0.227 2	0.457 4	0.728 1	0.974 0	1.281	1.772	2.883	
200	-0.014 2	0.234 3	0.456 2	0.720 0	0.958 7	1.251	1.704	2.648	6.923
250	+ 0.003 3	0.241 6	0.455 1	0.712 2	0.944 2	1.224	1.643	2.460	5.162
300	0.020 5	0.248 9	0.454 2	0.704 7	0.930 3	1.198	1.589	2.306	4.276
350	0.037 3	0.256 2	0.453 4	0.697 5	0.917 2	1.175	1.539	2.176	3.718
400	0.053 5	0.263 6	0.452 8	0.690 7	0.904 6	1.152	1.494	2.065	3.324
450	0.069 0	0.270 9	0.452 3	0.684 1	0.892 6	1.131	1.453	1.968	3.027
500	0.083 6	0.278 2	0.452 0	0.677 7	0.881 1	1.111	1.415	1.884	2.791
600	0.110 0	0.292 6	0.451 7	0.665 7	0.859 6	1.075	1.348	1.742	2.439
700	0.131 7	0.306 5	0.451 8	0.654 5	0.839 7	1.042	1.290	1.626	2.186
800	0.147 5	0.319 6	0.452 3	0.644 1	0.821 3	1.012	1.238	1.530	1.994
900	0.156 5	0.331 7	0.453 0	0.634 3	0.804 2	0.984 4	1.193	1.448	1.843
1 000	0.157 6	0.342 6	0.454 0	0.625 2	0.788 2	0.959 4	1.152	1.377	1.720

^a β in $10^{-3}/\text{K}$.**Table 5 Thermal conductivity λ of liquid water as a function of pressure and temperature"**

Pressure, bar	Temperature, °C								
	0	20	50	100	150	200	250	300	350
1	569	604	643						
10	570	604	644	681	687				
50	573	608	647	684	690	668	618		
100	577	612	651	688	693	672	625	545	
150	581	616	655	691	696	676	633	559	
200	585	620	659	695	700	681	639	571	454
250	589	623	662	698	703	685	646	582	476
300	592	627	666	701	706	689	652	592	496
350	596	630	669	704	710	693	657	601	514
400	599	634	672	707	713	697	662	609	529
450	603	637	675	710	716	701	667	616	541
500	606	640	678	713	720	704	671	622	552

^a λ in 10^{-3} W/m K .

Table 6 Dynamic viscosity η of liquid water as a function of pressure and temperature^a

Pressure, bar	Temperature, °C								
	0	20	50	100	150	200	250	300	350
1	1 750.0	1 000.0	544.0						
10	1 750.0	1 000.0	544.0	279.0	181.0				
50	1 750.0	1 000.0	545.0	280.0	182.0	135.0	107.0		
100	1 750.0	1 000.0	545.0	281.0	183.0	136.0	109.0	90.5	
150	1 740.0	1 000.0	546.0	282.0	184.0	137.0	110.0	91.7	
200	1 740.0	999.0	546.0	283.0	185.0	138.0	111.0	93.0	73.0
250	1 740.0	999.0	547.0	284.0	187.0	139.0	112.0	94.3	75.9
300	1 740.0	998.0	547.0	285.0	188.0	141.0	113.0	95.5	78.5
350	1 730.0	997.0	548.0	286.0	189.0	142.0	115.0	96.8	80.2
400	1 730.0	997.0	548.0	287.0	190.0	143.0	116.0	98.1	82.1
450	1 730.0	996.0	549.0	288.0	191.0	144.0	117.0	99.3	83.6
500	1 720.0	996.0	549.0	289.0	192.0	145.0	118.0	101.0	84.8

^a η in 10^{-6} kg/m s.**Table 7 Kinematic viscosity ν of liquid water as a function of pressure and temperature^a**

Pressure, bar	Temperature, °C								
	0	20	50	100	150	200	250	300	350
1	1.75	1.00	0.551						
10	1.75	1.00	0.550	0.291	0.197				
50	1.75	1.00	0.550	0.292	0.198	0.156	0.134		
100	1.74	0.998	0.549	0.292	0.198	0.156	0.135	0.126	
150	1.73	0.995	0.549	0.292	0.199	0.157	0.136	0.126	
200	1.72	0.992	0.548	0.293	0.199	0.157	0.136	0.127	0.122
250	1.72	0.990	0.548	0.293	0.201	0.158	0.136	0.127	0.121
300	1.72	0.987	0.547	0.293	0.202	0.159	0.137	0.127	0.122
350	1.70	0.984	0.547	0.294	0.202	0.160	0.138	0.128	0.122
400	1.70	0.981	0.545	0.294	0.203	0.160	0.139	0.128	0.122
450	1.69	0.978	0.545	0.294	0.203	0.161	0.139	0.129	0.122
500	1.68	0.977	0.544	0.295	0.204	0.162	0.140	0.130	0.122

^a ν in 10^{-6} m²/s.**Table 8 Prandtl number of liquid water as a function of pressure and temperature**

Pressure, bar	Temperature, °C								
	0	20	50	100	150	200	250	300	350
1	13.0	6.94	3.54						
10	13.0	6.93	3.53	1.73	1.14				
50	12.8	6.86	3.51	1.72	1.13	0.902	0.842		
100	12.6	6.79	3.48	1.71	1.13	0.899	0.831	0.940	
150	12.4	6.72	3.46	1.71	1.13	0.896	0.820	0.899	
200	12.3	6.65	3.43	1.70	1.13	0.893	0.812	0.866	1.31
250	12.1	6.59	3.41	1.69	1.13	0.891	0.805	0.840	1.12
300	11.9	6.52	3.38	1.69	1.12	0.888	0.799	0.819	1.02
350	11.8	6.47	3.36	1.68	1.12	0.886	0.795	0.803	0.950
400	11.6	6.40	3.34	1.68	1.12	0.885	0.791	0.790	0.903
450	11.5	6.35	3.32	1.67	1.12	0.884	0.788	0.779	0.867
500	11.4	6.30	3.31	1.67	1.12	0.883	0.786	0.771	0.832

Table 9 Thermal diffusivity κ of liquid water as a function of pressure and temperature^a

Pressure, bar	Temperature, °C								
	0	20	50	100	150	200	250	300	350
1	0.135	0.144	0.156						
10	0.135	0.144	0.156	0.168	0.173				
50	0.137	0.146	0.157	0.170	0.175	0.173	0.159		
100	0.138	0.147	0.158	0.171	0.175	0.174	0.162	0.134	
150	0.140	0.148	0.159	0.171	0.176	0.175	0.166	0.140	
200	0.140	0.149	0.160	0.172	0.176	0.176	0.167	0.147	0.093
250	0.142	0.150	0.161	0.173	0.178	0.177	0.169	0.151	0.108
300	0.145	0.151	0.162	0.173	0.180	0.179	0.171	0.155	0.120
350	0.145	0.152	0.163	0.175	0.180	0.181	0.174	0.159	0.128
400	0.147	0.153	0.163	0.175	0.181	0.181	0.178	0.162	0.135
450	0.147	0.154	0.164	0.176	0.181	0.182	0.178	0.166	0.141
500	0.147	0.155	0.164	0.177	0.182	0.183	0.178	0.169	0.147

^a κ in $10^{-6} \text{ m}^2/\text{s}$.**BIBLIOGRAPHY FOR SECTION 5.5.3**

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2.2.4

Banks of plain and finned tubes

A. Žukauskas and R. Ulinskas

A. Introduction

In cross flow of real fluids over a single tube, a laminar boundary layer is developed from the front stagnation point and separates at some point around the circumference. This gives rise to a symmetric steady-state pair of vortices and a recirculation zone in the rear. When the Reynolds number[†] is greater than about 40, the flow in the recirculation zone becomes unstable and periodic vortex shedding commences in the rear, with separation of the laminar boundary layer at $\phi = 82^\circ$, where ϕ is the angle subtended at the tube axis by the stagnation and separation points. With a further increase of Re, a critical flow regime is reached at $Re > 2 \times 10^5$, characterized by a laminar-turbulent transition in the boundary layer preceding the separation point, which is shifted downstream to $\phi = 140^\circ$. The frequency of vortex shedding is determined from the Strouhal number $Sr = fd/u$, where f is the frequency of vortex shedding and d is the tube diameter. For practical purposes, Sr for a single tube may be taken as 0.2 in the Reynolds number range 300 to 2×10^5 . In the critical region, the value of Sr increases to 0.46 and then decreases to 0.27 [1] at $Re = 3.5 \times 10^6$. For an incompressible fluid, velocity and pressure variations outside the boundary layer are conveniently described by the Bernoulli equation:

[†]The Reynolds number is defined as ud/ν , where d is the tube diameter, ν is the kinematic viscosity, and u is the upstream velocity ($=u_b$) for single tubes and the maximum intertube velocity for tube banks.

$$p_b + \frac{\rho u_b^2}{2} = p_x + \frac{\rho u_x^2}{2} = \text{const} \quad (1)$$

The quantities are defined in Fig. 1; u_x is the peripheral local velocity on the tube, p_x and p_b are the local and main flow pressures, and ρ is the fluid mass density. Thus,

$$u_x = u_b \sqrt{1 - \frac{p_x - p_b}{\rho u_b^2/2}} \quad (2)$$

If a tube is placed in a bank, the pattern of flow around it is by no means similar to that on a single tube. The detailed differences of the flow pattern are determined by the bank arrangement, bank geometry, tube location, and Reynolds number. The two most common arrangements are in line or staggered (see Fig. 2). The geometry is described by the parameters

$$a = \frac{s_1}{d}$$

$$b = \frac{s_2}{d}$$

where a and b are the relative transverse and longitudinal pitches, respectively (see Fig. 2). Throughout the tube bundle, the pressure gradients, velocity distributions, and the recirculation zones in the rear of the tubes are affected by flow fluctuations.

The velocity distribution outside the boundary layer may be determined using the Bernoulli equation, Eq. (2), from the measured pressure distribution values around the tube. A comparison in Fig. 1 illustrates the different pressure distributions (which give rise to

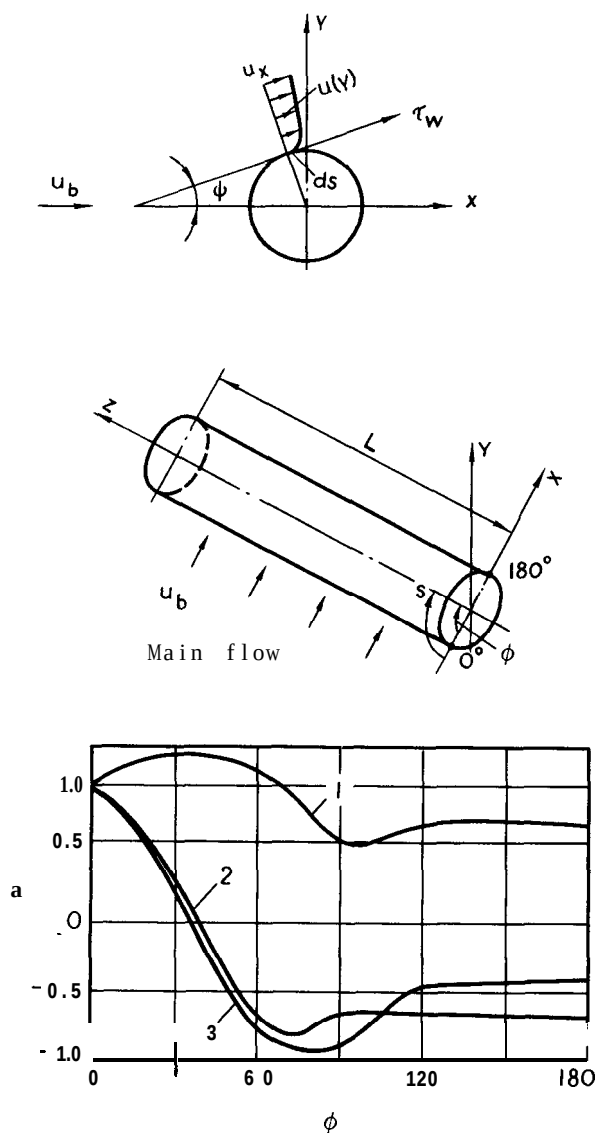


Figure 1 Pressure coefficient distribution around a tube at $Re = 10^4$. (1) In-line bank, inner row. (2) Single tube. (3) Staggered bank, inner row.

different velocity distributions) on a single tube and on a tube in a bank in cross flow. In banks of in-line arrangement, a maximum pressure is observed at $\phi = 40^\circ$, which is the point at which the flow from the upstream tube impacts. In staggered banks, the pressure on the front part of each separate tube is similar to that on a single tube. A pressure coefficient for a tube in a bank may be defined as

$$P = 1 - \frac{p_{\phi=0} - p_{\phi}}{\frac{1}{2}\rho u^2} \quad (3)$$

where u is the mean velocity in the minimum intertube space [see Eq. (4)], $p_{\phi=0}$ is the pressure at the front stagnation point, and p_{ϕ} is the pressure at angle ϕ .

The flow pattern surrounding a tube in a tube

bank is a function of Reynolds number Re . In the lower range of Re , the laminar boundary layer develops similarly to that on a single tube, with a separation at $\phi \approx 90^\circ$ and with circulation vortices in the rear. Intertube spaces are occupied mainly by a laminar flow and by macroscale vortices in the recirculation zones. The effects of these macroscale vortices on the laminar layers on the front parts of the neighboring tubes are fully eliminated by viscous forces and by the negative pressure gradients. Such a pattern of flow, which is observed at $Re < 10^3$, is described as a predominantly laminar one.

With a further increase of Re , the intertube flow becomes highly turbulent. The degree of turbulence is a function of bank configuration geometry (a and b) and Re . Turbulence increases with distance into the bank, becoming fully developed in about the third or fourth row. Notwithstanding the surrounding turbulence, a laminar boundary layer still develops on the tubes in the inner rows. This pattern of flow may be observed up to $Re = 10^5$ and higher.

In tube banks characterized by $(2b^2 - 0.5) < a$, a separation bubble and reattachment of the laminar boundary layer may be observed at Reynolds numbers as low as 10^4 . This causes intensive turbulence in the boundary layer in the rear zone. With a further increase of Re , to the range $10^5 - 2 \times 10^5$ (depending on the geometry), a laminar/turbulent transition occurs in the boundary layer before its separation at $\phi = 140^\circ$. Here we have the so-called critical flow regime. Increasing Re to 10^6 leads to the creation of the supercritical regime, with a highly turbulent flow and a developed turbulent boundary layer. Significant changes are also noted in the distribution of pressures in the supercritical regime. At $Re > 10^6$, the flow patterns and the pressure distributions are similar in

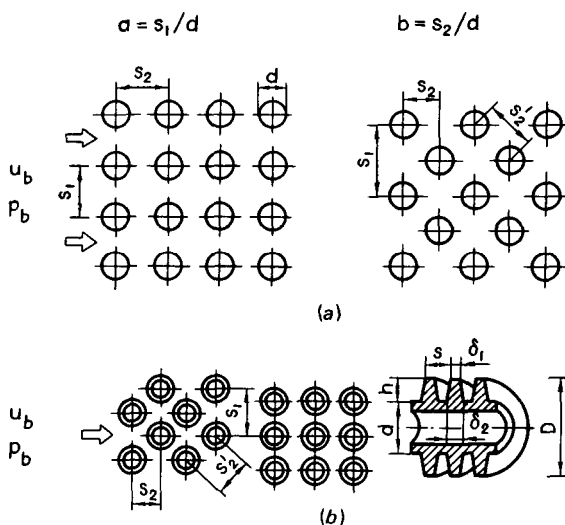


Figure 2 Tube arrangements in banks. (a) Plain tubes. (b) Finned tubes.

both staggered and in-line banks (Fig. 3). A decrease of P is noted in the region from the impact point to 90° , accompanied by flow acceleration outside the boundary layer. In the rear, P increases (with a decrease of outer velocity), leading to the separation of the turbulent boundary layer. No significant changes of pressure are noted in the recirculation zone.

The increase in intertube velocity is determined mainly by the relative transverse pitch a . The value of u increases significantly with a decrease of a . Mean velocity in the minimum intertube space is determined by

$$u = u_b \frac{a}{(a-1)} \quad (4)$$

if $a \leq 2b^2 - 0.5$. In compact banks, the minimum intertube space may occur in the diagonal direction (see Fig. 2) if $a > 2b^2 - 0.5$. In this case,

$$u = u_b \frac{a}{2\sqrt{(a^2/4) + b^2} - 1} \quad (5)$$

and in an arbitrary position by

$$u(\phi) = u_b \frac{a}{a - \sin \phi} \quad (6)$$

B. Drag and pressure drop in banks of tubes

In flow through tube banks, there occur irreversible energy changes due to friction. These energy changes are manifested as pressure losses over the bank. The calculation of these pressure changes is vital to the design of the circulation system (pumps, fans, natural circulation). Conversely, the energy changes are associated with forces in the individual tubes in the bank. These forces are important in assessing and calculating phenomena such as tube vibration. Although the pressure losses and forces on the tubes are clearly linked, it

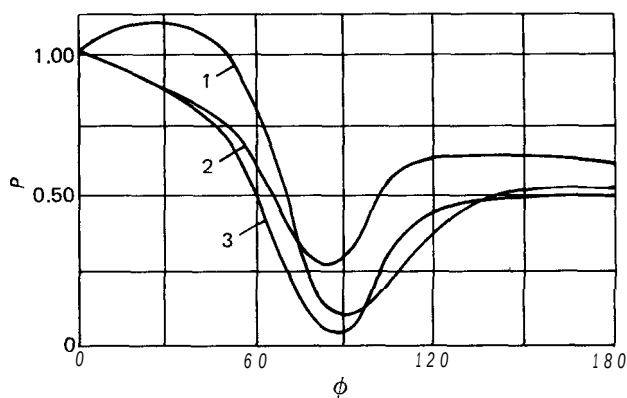


Figure 3 Pressure coefficient distribution around a tube. (1) In-line bank, $Re = 6 \times 10^5$. (2) Staggered bank, $Re = 10^6$. (3) In-line bank, $Re = 10^6$, inner rows.

is convenient to treat them separately in the present context, dealing first with the forces on the tubes.

(a) Drag on a tube in a bank

Flow of a fluid through a tube bank generates a force on each separate tube, the direction of which is not necessarily coincident with that of the flow. The total drag force is the sum of the skin friction and the form drag. Its longitudinal component is known as the drag force F_x and the transverse component as the lift force F_y . The forces on a tube in a bank may be described in terms of the skin friction coefficient c_f and the drag coefficient c_D . The skin friction coefficient is defined [2, 3] by

$$c_f = \frac{2\tau_{wx}}{\rho u^2} \quad (7)$$

where τ_{wx} is the mean horizontal component of the shear stress on the tube surface. The local shear stress is given by

$$\tau_w = \eta \left(\frac{\partial u}{\partial y} \right)_{y=0} \quad (8)$$

where η is the dynamic (absolute) viscosity and $(\partial u / \partial y)_{y=0}$ is the velocity gradient at the wall (see Fig. 1). If the velocity distribution in the boundary layer is known, τ_{wx} may be obtained by integration along the perimeter from the front stagnation point either to the rear stagnation point or to the separation point:

$$\tau_{wx} = \frac{1}{s} \int_{s=0}^s \tau_w dX \quad (9)$$

where $dX = \cos \psi ds$, ψ being the angle of the main flow direction to the tube surface tangent (see Fig. 1), and s is peripheral distance. For nonseparating flows, integration is performed from the impact point up to the rear stagnation point. For separating flows, the integration terminates at the separation point. The point at which $\partial u / \partial y = 0$ is defined as the point of separation. To determine shear stress from Eq. (9) for Re from 2 to 10^5 , the impact point is assumed for staggered banks at $\phi = 0^\circ$, and for in-line banks is determined from experimental data (Fig. 4).

To assist in solving Eq. (9), a correlation of local friction $c_f = 2\tau_w / \rho u^2$ may be used as illustrated in Fig. 5.

Skin friction accounts for nearly all of F_x at low Re . With increasing Re , the skin friction contribution decreases as a fraction of F_x , the remaining force being form drag. In the critical flow regime the skin friction might contribute typically 0.5-2% of the total force. It is convenient to define a drag coefficient c_D in terms

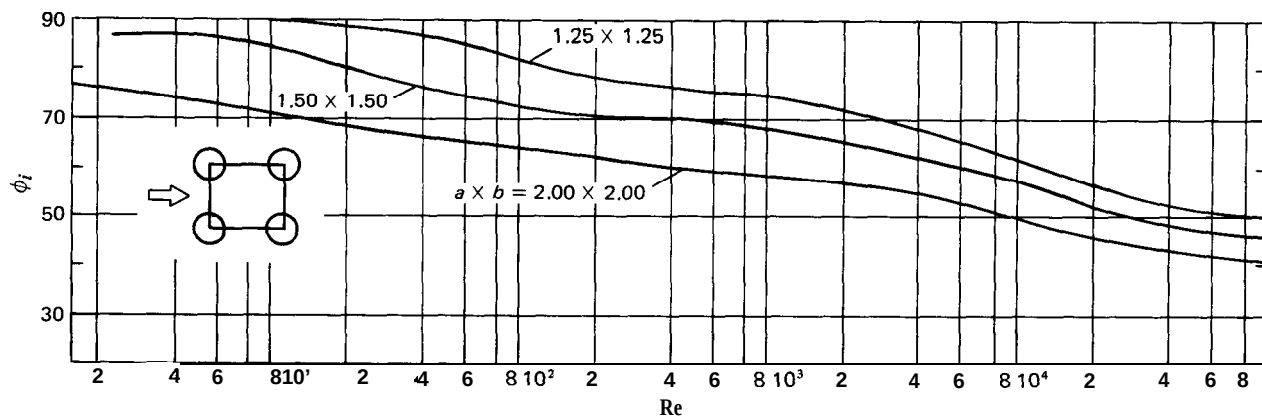


Figure 4 The point of flow impact.

of the total force F_x (i.e., including **both** skin friction and form drag) as follows:

$$c_D = \frac{2F_x}{\rho u^2 A_{tr}} \quad (10)$$

where A_{tr} is the tube cross-sectional area transverse to the flow ($= L \times d$, where L is the tube length and d is the tube diameter). In order to determine F_x for a given tube, the pressure p is measured at the surface at a number (n_0 , say) of uniformly distributed points. F_x is then given by

$$F_x = A A \sum_{i=1}^{n_0} p_i \cos \phi_i \quad (11)$$

where

$$\Delta A = \pi \frac{dL}{n_0} \quad (12)$$

where L is the length of the tube and d is the tube diameter.

Figure 6 gives the drag coefficient for the first row for in-line and staggered banks of plain tubes with

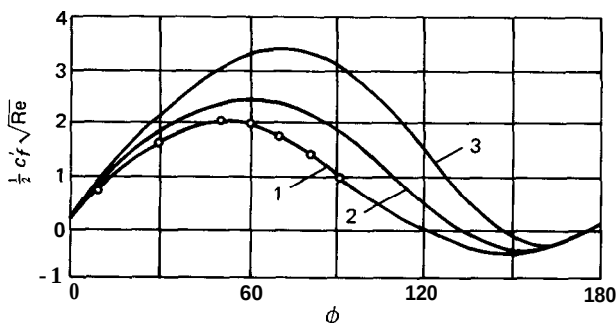


Figure 5 Skin friction coefficient in staggered banks as a function of angle. (0) Analytical to the separation point. (1) Experimental, bank 1.50 X 1.50 with Re = 1 017 (authors). (2) Re = 1.3 X 10⁵. (3) Re = 1.4 X 10⁶, bank 2.0 X 1.4 [2].

$a \times b = 2.0 \times 2.0$ (curves 1 and 2), together with the drag coefficient of a compact bank $a \times b = 1.65 \times 1.53$ of helical-finned tubes for the first row (curves 3 and 4) and one of the inner rows (curves 5 and 6).

The following equations are recommended for co.

In-line banks, $10^2 < Re < 4 \times 10^3$:

$$c_D = 0.535 \exp(5.378 Re^{-0.345}) \quad (13)$$

Staggered banks, $10^2 < Re < 4 \times 10^3$:

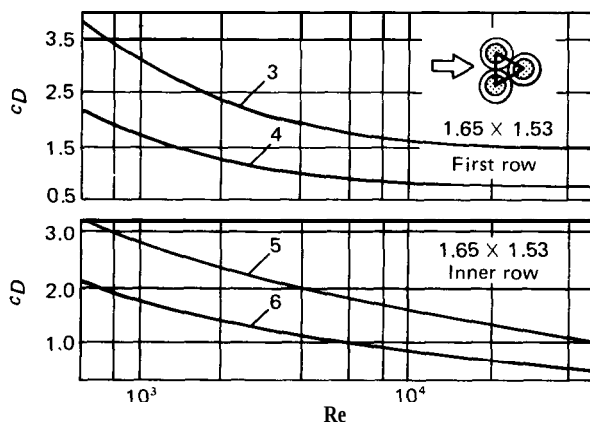
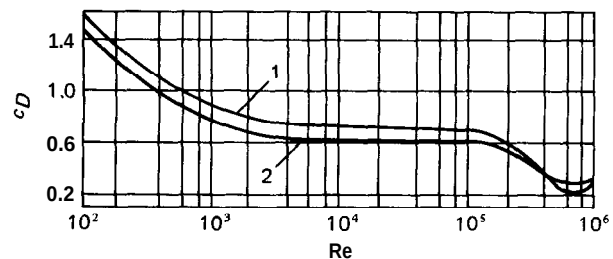


Figure 6 Drag coefficient of a tube as a function of Re. (1) In line. (2) Staggered bank, 2.0 X 2.0, plain tubes, first row. (3, 4) Staggered bank, 1.65 X 1.53, first row. (5, 6) Staggered bank, 1.65 X 1.53, inner row. $D = 25$, $d = 15$, $h = 5$, $s = 3$, $\delta_1 = 0.4$, $\delta_2 = 3.0$ mm. The attack angle of fins equals 3°.

$$c_D = 0.417 \exp (4.932 \operatorname{Re}^{-0.296}) \quad (14)$$

In-line banks, $4 \times 10^3 < \operatorname{Re} < 6 \times 10^4$:

$$c_D = 0.735 - 0.411 \times 10^{-6} \operatorname{Re} \quad (15)$$

Staggered banks, $4 \times 10^3 < \operatorname{Re} < 6 \times 10^4$:

$$c_D = 0.647 - 0.5 \times 10^{-6} \operatorname{Re} \quad (16)$$

In-line banks, $6 \times 10^4 < \operatorname{Re} < 10^6$:

$$c_D = 0.621 + 0.169 \times 10^{-5} \operatorname{Re} - 11.343 \times 10^{-12} \operatorname{Re}^2 + 16,656 \times 10^{-18} \operatorname{Re}^3 - 7.377 \times 10^{-24} \operatorname{Re}^4 \quad (17)$$

Staggered banks, $6 \times 10^4 < \operatorname{Re} < 10^6$:

$$c_D = 0.618 + 0.491 \times 10^{-6} \operatorname{Re} - 6.303 \times 10^{-12} \operatorname{Re}^2 + 10.694 \times 10^{-18} \operatorname{Re}^3 - 5.2 \times 10^{-24} \operatorname{Re}^4 \quad (18)$$

Typical results for c_D in a finned-tube bank are illustrated in Fig. 6. The values depend on the definition of A_{fr} in the formula for calculating c_D [Eq. (10)] ; either the fin tip diameter may be used or the base tube diameter.

For the first row of tubes, the value c_D based on the fin tip diameter is given by (curve 3 of Fig. 6)

$$c_D = 1.45 \frac{1908.9}{\operatorname{Re}} - \frac{275.6 \times 10^3}{\operatorname{Re}^2} \quad (19)$$

and c_D based on the base tube diameter (curve 4) is given by

$$c_D = 0.706 + \frac{11909}{\operatorname{Re}} - \frac{215.4 \times 10^3}{\operatorname{Re}^2} \quad (20)$$

For an inner row of a bank of finned tubes, the value of c_D based on fin tip diameter is given by (curve 5)

$$c_D = 16.03 \operatorname{Re}^{-0.256} \quad (21)$$

and c_D based on base tube diameter (curve 6) is given by

$$c_D = 24.37 \operatorname{Re}^{-0.388} \quad (22)$$

(b) Pressure drop in banks of tubes

I. Form of correlating equations

The pressure drop Δp for flow through a bank of tubes is a function of the geometry (expressed in terms of s_1, s_2 , and d -see Fig. 2), the number of tube rows in the bank z , the flow velocity u , and the physical properties of the fluid:

$$\Delta p = f(u, s_1, s_2, d, z, \eta, \rho) \quad (23)$$

where η is the dynamic (absolute) viscosity. It is convenient, in what follows, to define u as the velocity at the minimum intertube gap. That is, u is the maximum velocity attained by the fluid as it passes through the various gaps between the tubes. Suppose that u_b is the superficial velocity through the tube bank (i.e., the volume flux of the fluid per unit face area-including tubes and intertube spaces-of the tube bank). It then follows that $u = u_b s_1 / (s_1 - d)$ for in-line banks and that u is either $u_b s_1 / (s_1 - d)$ or $u_b s_1 / 2(s_2' - d)$ (see Fig. 2 for definitions), depending on which is greater, for staggered banks. The velocities are expressed in terms of a and b through Eqs. (4) and (5).

Equation (23) may be written in dimensionless form:

$$\operatorname{Eu} = f(\operatorname{Re}, a, b, z) \quad (24)$$

where $\operatorname{Re} = ud/\nu$, $a = s_1/d$, and $b = s_2/d$. The Euler number, Eu , is related to pressure drop by

$$\Delta p = \operatorname{Eu} \frac{\rho u^2}{2} z \quad (25)$$

where z is the number of tube rows. The relation between friction factor f and Euler number is

$$f = \frac{2\Delta p p}{4\dot{m}^2 z} = \frac{1}{4} \operatorname{Eu} \quad (26)$$

where $\dot{m}$ is the mass flux, given by $\dot{m} = \rho u = \dot{M}/S$, where $\dot{M}$ is the mass flow rate of flow and S is the cross-sectional area for flow corresponding to the minimum intertube gap.

Data from a variety of sources [1, 4-10] have been plotted in Figs. 7 and 8 for in-line and staggered banks of tubes, respectively. These plots are in the form Eu/k_1 versus Re , where k_1 is a parameter accounting for geometry that will be introduced later. It will be seen from Figs. 7 and 8 that good agreement is obtained among the various data sources.

Traditionally, the most widely used form of relationship is of the power law form:

$$\operatorname{Eu} = k_2 \operatorname{Re} \quad (27)$$

where k_2 and r are constants that are functions of system geometry. Examples of this type of relationship are as follows.

1. Equations for in-line banks for the Reynolds number range $10^4 - 2 \times 10^5$

For $(b - 0.8)/(a - 1) \geq 1$:

$$\operatorname{Eu} = 0.52 \left(\frac{b - 0.8}{a - 1} \right)^{1.5} \operatorname{Re}^r \quad (28)$$

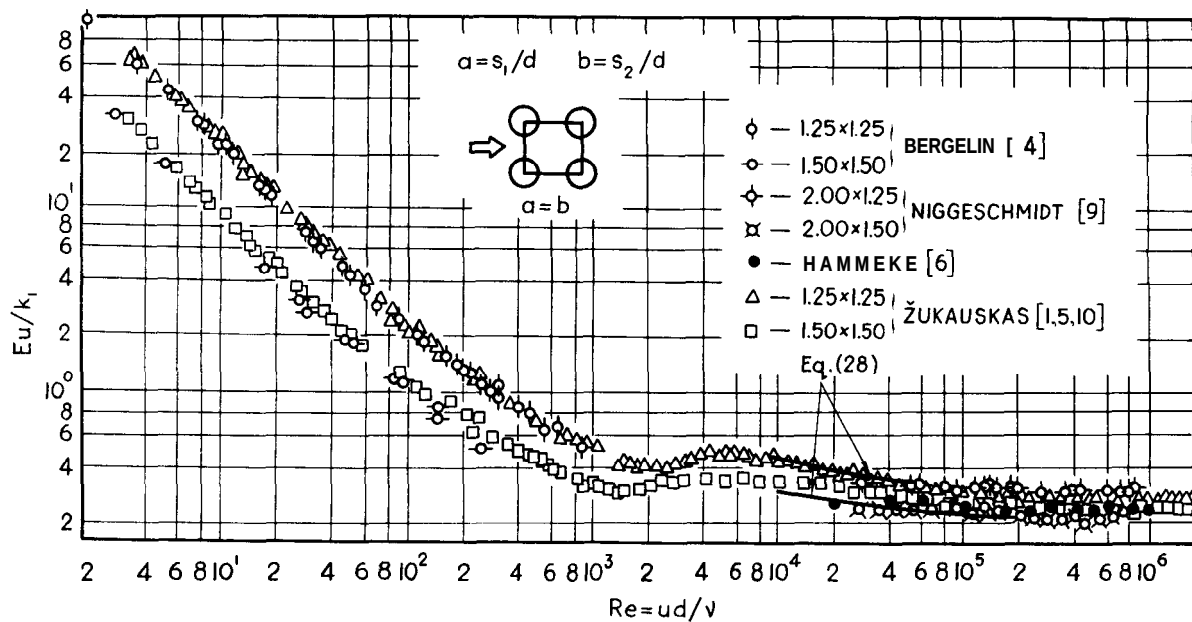


Figure 7 Pressure drop of in-line banks.

For $(b - 0.8)/(a - 1) \leq 1$:

$$Eu = 0.52 \left(\frac{b - 0.8}{a - 1} \right) Re^r \quad (29)$$

The exponent r is given by

$$r = 0.12 \left(\frac{b - 1}{a - 1} \right)^{0.5} \quad (30)$$

2. Equations for staggered, equilateral triangular banks

For $6 \times 10^2 < Re < 7 \times 10^3$:

$$Eu = 1.42 \left(\frac{1}{a - 1} \right)^{0.33} Re^{-0.15} \quad (31)$$

For $7 \times 10^3 < Re < 2 \times 10^5$:

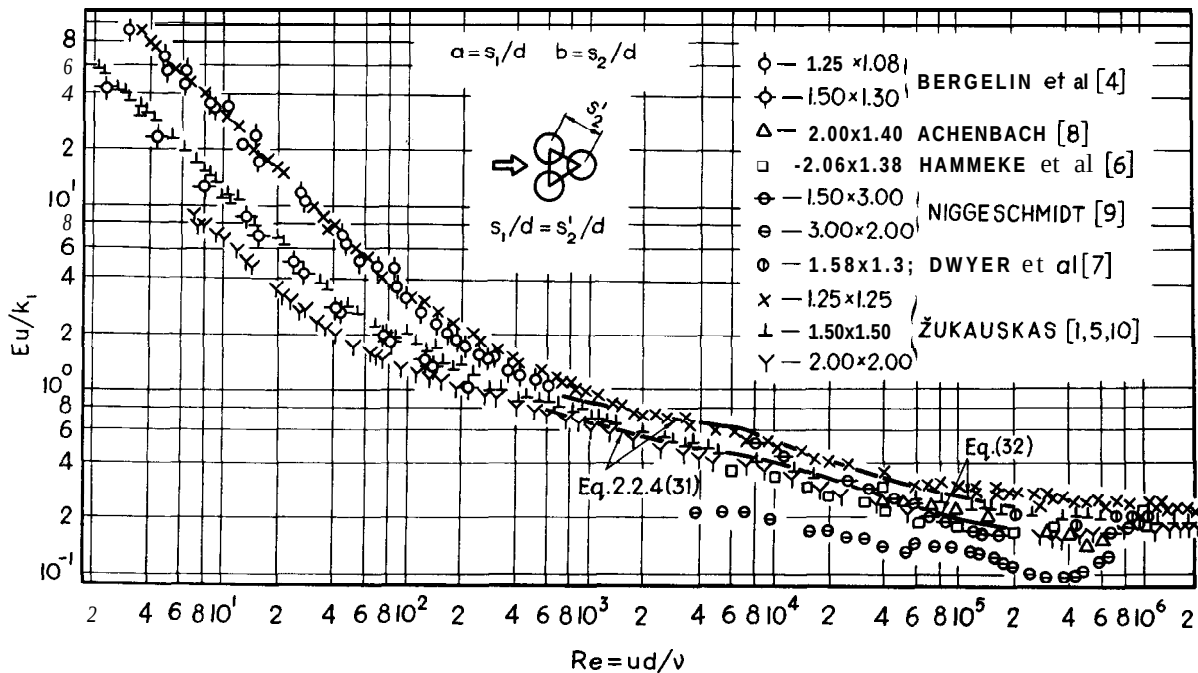


Figure 8 Pressure drop of staggered banks.

$$Eu = 5.2 \left(\frac{1}{a-1} \right)^{0.25} Re^{-0.29} \quad (32)$$

To compare Eqs. (28)-(32) with the experimental data shown in Figs. 7 and 8, Eu values were calculated from the equations and Eu/k_1 estimated using the relationships for k_1 to be given below (note that $k_1 \cong 1$ for the examples cited above). The resultant lines are shown in the figures and demonstrate the good agreement between Eqs. (28)-(32) and the experimental data. However, equations of the form of Eq. (27) can cover only limited ranges of data and are not recommended here. The recommended equations (to be introduced later) are in the form of an inverse power series, and separate ranges of equations are given for in-line and staggered banks, respectively. These equations are for banks with many transverse flows; corrections for lower members of rows are introduced later, as is a general rule to the utilization of the equations.

II. Recommended relationships for in-line tube banks

The recommended [5] curves for Eu/k_1 versus Re are shown graphically in Fig. 9. These curves are for tube banks having many rows (correction factors for banks with small numbers of rows are given later) and are fitted by inverse power series relationships, different relationships being used depending on the value of b (ratio of longitudinal pitch to diameter) and on the Reynolds number range. The appropriate equations are as follows:

For $b = 1.25$, $3 < Re < 2 \times 10^3$:

$$\frac{Eu}{k_1} = 0.272 + \frac{0.207 \times 10^3}{Re} + \frac{0.102 \times 10^3}{Re^2} - \frac{0.286 \times 10^3}{Re^3} \quad (33)$$

For $b = 1.25$, $2 \times 10^3 < Re < 2 \times 10^4$:

$$\frac{Eu}{k_1} = 0.267 + \frac{0.249 \times 10^4}{Re} - \frac{0.927 \times 10^7}{Re^2} + \frac{0.10 \times 10^{11}}{Re^3} \quad (34)$$

For $b = 1$ SO, $3 < Re < 2 \times 10^3$:

$$\frac{Eu}{k_1} = 0.263 + \frac{0.867 \times 10^2}{Re} - \frac{0.202 \times 10}{Re^2} \quad (35)$$

For $b = 1.50$, $2 \times 10^3 < Re < 2 \times 10^6$:

$$\frac{Eu}{k_1} = 0.235 + \frac{0.197 \times 10^4}{Re} - \frac{0.124 \times 10^8}{Re^2} + \frac{0.312 \times 10^{11}}{Re^3} - \frac{0.274 \times 10^{14}}{Re^4} \quad (36)$$

For $b = 2.0$, $7 < Re < 800$:

$$\frac{Eu}{k_1} = 0.188 + \frac{0.566 \times 10^2}{Re} - \frac{0.646 \times 10^3}{Re^2} + \frac{0.601 \times 10^4}{Re^3} - \frac{0.183 \times 10^5}{Re^4} \quad (37)$$

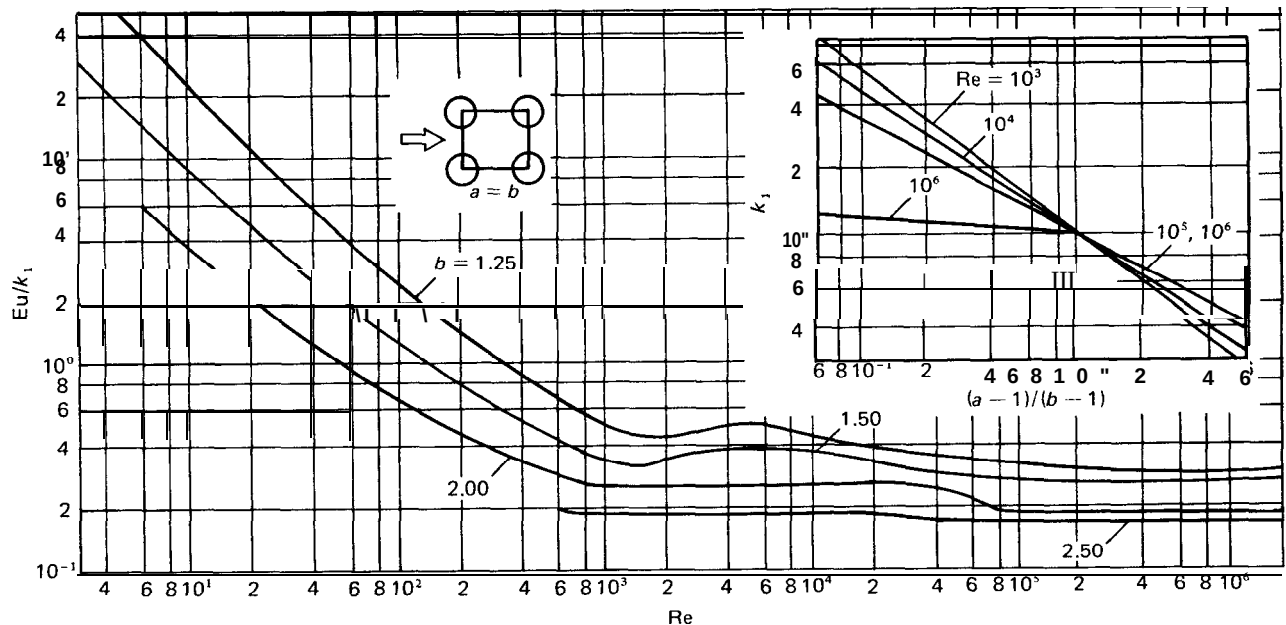


Figure 9 Pressure drop of in-line banks as referred to the relative longitudinal pitch b .

For $b = 2.0$, $800 < Re < 2 \times 10^6$:

$$\frac{Eu}{k_1} = 0.247 - \frac{0.595 Re}{10^6} + \frac{0.15 Re^2}{10} - \frac{0.137 Re^3}{10} + \frac{0.396 Re^4}{10^{24}} \quad (38)$$

For $b = 2.5$, $600 < Re < 2 \times 10^5$:

$$\frac{Eu}{k_1} = 0.177 - 0.311 \times 10^{-6} Re + 0.117 \times 10^{-11} Re^2 \quad (39)$$

To utilize these equations in calculating Euler numbers, values of the geometry parameter k_1 are needed, and curves for k_1 are also included in Fig. 9. It should be noted from that figure that $k_1 \approx 1$ when $a = b$, that is, when the longitudinal and transverse pitches are equal (a square array). For $a \neq b$, the values of k_1 is a function of $(a-1)/(b-1)$, the relationship being dependent on Reynolds number as follows (for the range $0.06 < (a-1)/(b-1) < 6$):

$$k_1 = 1.009 \left(\frac{a-1}{b-1} \right)^{-0.744} \quad \text{for } Re = 10^3 \quad (40)$$

$$k_1 = 1.007 \left(\frac{a-1}{b-1} \right)^{-0.655} \quad \text{for } Re = 10^4 \quad (41)$$

$$k_1 = 1.004 \left(\frac{a-1}{b-1} \right)^{-0.539} \quad \text{for } Re = 10^5 \quad (42)$$

$$k_1 = 1.218 - 0.297 \left(\frac{a-1}{b-1} \right) + 0.0265 \left(\frac{a-1}{b-1} \right)^2 \quad (43)$$

for $Re = 10^6$

For $Re = 10^7$, k_1 should be taken as unity.

III. Recommended relationships for staggered tube banks

For staggered tube banks, the recommended [5] curves for banks with many rows of tubes are shown in Fig. 10 with the ratio of the transverse pitch to tube diameter (a) as a parameter. These curves are fitted by inverse power series whose constants depend on the value of a and on the Reynolds number range as follows.

For $a = 1.25$, $3 < Re < 10^3$:

$$\frac{Eu}{k_1} = 0.795 + \frac{0.247 \times 10^3}{Re} + \frac{0.335 \times 10^3}{Re^2} - \frac{0.155 \times 10^4}{Re^3} + \frac{0.241 \times 10^4}{Re^4} \quad (44)$$

For $a = 1.25$, $10^3 < Re < 2 \times 10^6$:

$$\frac{Eu}{k_1} = 0.245 + \frac{0.339 \times 10^4}{Re} + \frac{0.984 \times 10^7}{Re^2} + \frac{0.132 \times 10^{11}}{Re^3} + \frac{0.599 \times 10^{13}}{Re^4} \quad (45)$$

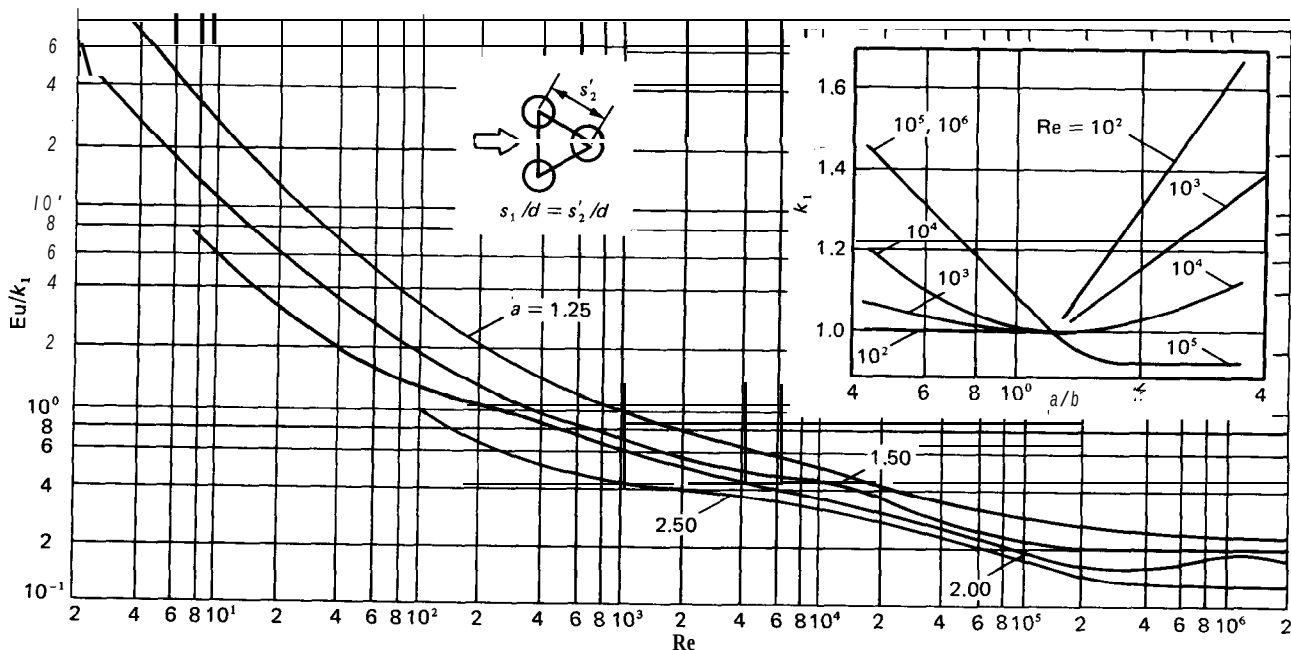


Figure 10 Pressure drop of staggered banks as referred to the relative transverse pitch a .

For $a = 1.5$, $3 < \text{Re} < 10^3$:

$$\frac{\text{Eu}}{k_1} = 0.683 + \frac{0.111 \times 10^3}{\text{Re}} - \frac{0.973 \times 10^2}{\text{Re}^2} + \frac{0.426 \times 10^3}{\text{Re}^3} - \frac{0.574 \times 10^3}{\text{Re}^4} \quad (46)$$

For $a = 1.5$, $10^3 < \text{Re} < 2 \times 10^6$:

$$\frac{\text{Eu}}{k_1} = 0.203 + \frac{0.248 \times 10^4}{\text{Re}} - \frac{0.758 \times 10^7}{\text{Re}^2} + \frac{0.104 \times 10^{11}}{\text{Re}^3} - \frac{0.482 \times 10^{13}}{\text{Re}^4} \quad (47)$$

For $a = 2.0$, $7 < \text{Re} < 10^2$:

$$\frac{\text{Eu}}{k_1} = 0.713 + \frac{0.448 \times 10^2}{\text{Re}} - \frac{0.126 \times 10^3}{\text{Re}^2} - \frac{0.582 \times 10^3}{\text{Re}^3} \quad (48)$$

For $a = 2.0$, $10^2 < \text{Re} < 10^4$:

$$\frac{\text{Eu}}{k_1} = 0.343 + \frac{0.303 \times 10^3}{\text{Re}} - \frac{0.717 \times 10^5}{\text{Re}^2} + \frac{0.88 \times 10^7}{\text{Re}^3} - \frac{0.38 \times 10^9}{\text{Re}^4} \quad (49)$$

For $a = 2.0$, $10^4 < \text{Re} < 2 \times 10^6$:

$$\frac{\text{Eu}}{k_1} = 0.162 + \frac{0.181 \times 10^4}{\text{Re}} + \frac{0.792 \times 10^8}{\text{Re}^2} - \frac{0.165 \times 10^{13}}{\text{Re}^3} + \frac{0.872 \times 10^{16}}{\text{Re}^4} \quad (50)$$

For $a = 2.5$, $10^2 < \text{Re} < 5 \times 10^3$:

$$\frac{\text{Eu}}{k_1} = 0.33 + \frac{0.989 \times 10^2}{\text{Re}} - \frac{0.148 \times 10^5}{\text{Re}^2} + \frac{0.192 \times 10^7}{\text{Re}^3} - \frac{0.862 \times 10^8}{\text{Re}^4} \quad (51)$$

For $a = 2.5$, $5 \times 10^3 < \text{Re} < 2 \times 10^6$:

$$\frac{\text{Eu}}{k_1} = 0.119 + \frac{0.498 \times 10^4}{\text{Re}} - \frac{0.507 \times 10^8}{\text{Re}^2} + \frac{0.251 \times 10^{12}}{\text{Re}^3} - \frac{0.463 \times 10^{15}}{\text{Re}^4} \quad (52)$$

Curves for the staggered array geometry factor k_1 are shown in the inset in Fig. 10. It is seen that the

value of k_1 depends on the ratio of the transverse to longitudinal pitch (a/b). Note that for an *equilateral triangular* array ($a/b = 1.155$), $k_1 \approx 1$. For other geometries, the following equations may be used:

For $0.5 < a/b < 1.2$, $\text{Re} = 10^3$:

$$k_1 = \left(\frac{a}{b}\right)^{-0.048} \quad (53)$$

For $0.45 < a/b < 3.5$, $\text{Re} = 10^4$:

$$k_1 = 1.28 \frac{0.708}{(a/b)} + \frac{0.55}{(a/b)^2} - \frac{0.113}{(a/b)^3} \quad (54)$$

For $0.45 < a/b < 3.5$, $\text{Re} = 10^5$ and $0.45 < a/b < 1.6$, $\text{Re} = 10^6$:

$$k_1 = 2.016 - 1.675 \left(\frac{a}{b}\right) + 0.948 \left(\frac{a}{b}\right)^2 - 0.234 \left(\frac{a}{b}\right)^3 + 0.021 \left(\frac{a}{b}\right)^4 \quad (55)$$

For $1.25 < a/b < 3.5$, $\text{Re} = 10^2$:

$$k_1 = 0.93 \left(\frac{a}{b}\right)^{0.48} \quad (56)$$

For $1.25 < a/b < 3.5$, $\text{Re} = 10^3$:

$$k_1 = 0.951 \left(\frac{a}{b}\right)^{0.284} \quad (57)$$

IV. Correction factors for pressure drop with small numbers of rows

The equations given above for Eu are for tube banks with large number of transverse rows. The pressure drop per tube row in the first few rows of tubes may be significantly different, and this effect has to be allowed for in banks with small numbers of tube rows. Defining an equivalent Euler number per tube row Eu_z as $\text{Eu}_z = \Delta p' / [(1/2)\rho u^2]$, where $\Delta p'$ is the pressure drop over tube row z , we may define a factor c_z such that $\text{Eu}_z = c_z \text{Eu}$, where Eu is given by the recommended equations. We may also define a factor C_z that relates the *average* Euler number Eu , for a bank of z rows with the Euler number calculated from the recommended equations; thus,

$$\text{Eu} = C_z \text{Eu} \quad \text{and} \quad C_z = \frac{1}{z} \sum_{z=1}^z c_z$$

Curves for c_z are given in Figs. 11 and 12 for in-line and staggered banks, respectively. These curves are fitted by the following equations:

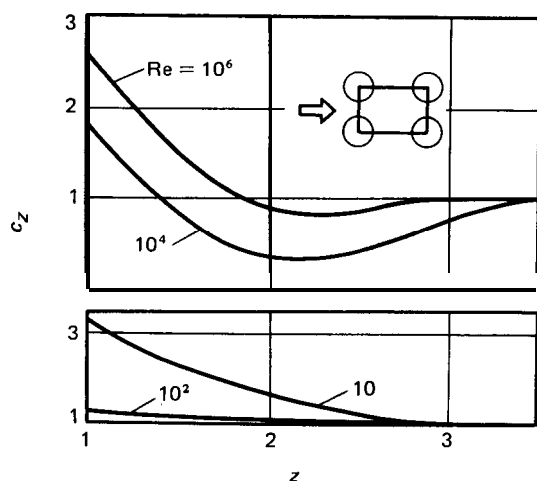


Figure 11 Factor for the number of rows for in-line bank, 2.0 X 2.0, of plain tubes.

For in-line banks:

For $Re = 10$,

$$c_z = \frac{3.879}{z + 0.091} - 0.215 \quad c_z = 1, z > 3 \quad (58)$$

For $Re = 10^2$,

$$c_z = 0.409 + \frac{5.049}{z + 5.006} \quad c_z = 1, z > 3 \quad (59)$$

For $Re = 10^4$,

$$c_z = 7.0 - 7.53z + 2.73z^2 - 0.305z^3 \quad c_z = 1, z > 4 \quad (60)$$

For $Re = 10^6$,

$$c_z = 8.16 - 8.314z + 3.303z^2 - 0.5223z^3 + 0.0253z^4 \quad c_z = 1, z > 6 \quad (61)$$

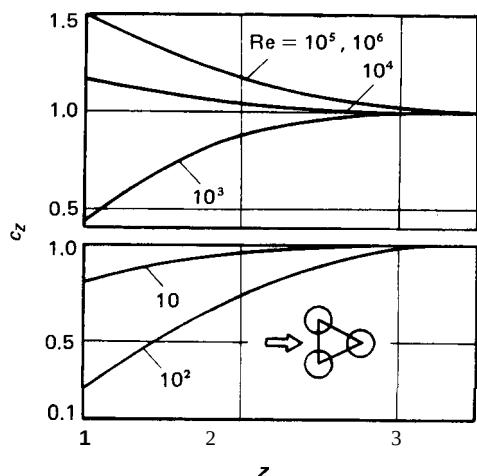


Figure 12 Factor for the number of rows for staggered banks, 2.0 X 2.0, of plain tubes.

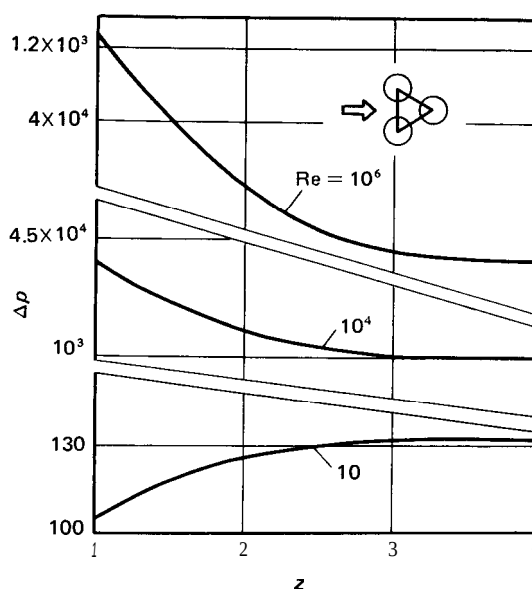


Figure 13 Pressure drop through the rows of a staggered bank, 2.0 X 2.0 (1) $Re = 10$, aviation oil at $T_b = 25^\circ\text{C}$, $\rho_b = 892.4$, $\nu_b = 671.8 \times 10^{-6}$. (2) $Re = 10^4$, transformer oil at $T_b = 50^\circ\text{C}$, $\rho_b = 879.9$, $\nu_b = 7.4 \times 10^{-6}$. (3) $Re = 10^6$, water at $T_b = 50^\circ\text{C}$, $\rho_b = 988.1$, $\nu_b = 0.556 \times 10^{-6}$.

For staggered banks:

For $Re = 10$,

$$c_z = 1.065 - \frac{0.180}{z - 0.297} \quad c_z = 1, z \geq 3 \quad (62)$$

For $Re = 10^2$,

$$c_z = 1.798 - \frac{3.497}{z + 1.273} \quad c_z = 1, z \geq 4 \quad (63)$$

For $Re = 10^3$,

$$c_z = 1.149 - \frac{0.411}{z - 0.412} \quad c_z = 1, z \geq 3 \quad (64)$$

For $Re = 10^4$,

$$c_z = 0.924 + \frac{0.269}{z + 0.143} \quad c_z = 1, z \geq 3 \quad (65)$$

For $Re = 10^5$ and 10^6 ,

$$c_z = 0.62 + \frac{1.467}{z + 0.667} \quad c_z = 1, z \geq 4 \quad (66)$$

The above equations are suitable for computer calculation, but for hand calculations it is preferable to use the table of values given as Table 1.

(c) Influence of fluid-property variation on pressure drop

I. Effect of wall-to-bulk viscosity variations

Since fluid physical properties depend on temperature, the fluid near the heated or cooled tube wall has

Table 1 Correction factors for row-to-row variations

		Number of rows z									
		1	2	3	4	5	6	7	8	9	10
In-line banks:											
Re = 10	$c_z =$	3.357	1.640	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
	$C_z =$	3.357	2.499	1.999	1.749	1.599	1.499	1.428	1.375	1.333	1.299
Re = 10^2	$c_z =$	1.250	1.130	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
	$C_z =$	1.250	1.190	1.127	1.09s	1.076	1.063	1.054	1.048	1.042	1.038
Re = 10^4	$c_z =$	1.895	0.420	0.745	1.000	1.000	1.000	1.000	1.000	1.000	1.000
	$C_z =$	1.895	1.157	1.020	1.015	1.012	1.010	1.009	1.008	1.007	1.006
Re = 10^6	$c_z =$	2.658	0.993	0.958	0.953	1.000	1.000	1.000	1.000	1.000	1.000
	$C_z =$	2.658	1.826	1.536	1.392	1.313	1.261	1.224	1.196	1.174	1.157
Staggered banks:											
Re = 10	$c_z =$	0.809	0.959	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
	$C_z =$	0.809	0.884	0.923	0.942	0.954	0.961	0.967	0.971	0.974	0.977
Re = 10^2	$c_z =$	0.260	0.730	0.980	1.000	1.000	1.000	1.000	1.000	1.000	1.000
	$C_z =$	0.260	0.495	0.657	0.743	0.794	0.838	0.853	0.871	0.886	0.897
Re = 10^3	$c_z =$	0.450	0.890	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
	$C_z =$	0.450	0.670	0.780	0.835	0.868	0.890	0.906	0.917	0.927	0.934
Re = 10^4	$c_z =$	1.159	1.050	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
	$C_z =$	1.159	1.105	1.070	1.052	1.042	1.035	1.030	1.026	1.023	1.021
Re = $10^5, 10^6$	$c_z =$	1.500	1.170	1.020	1.000	1.000	1.000	1.000	1.000	1.000	1.000
	$C_z =$	1.500	1.335	1.230	1.173	1.138	1.115	1.099	1.086	1.077	1.069

different properties than the bulk fluid. This affects the pressure drop and the Euler number Eu_T for the case where there is a temperature drop may be calculated from the Euler number (Eu) for uniform temperature as follows:

$$Eu_T = Eu \left(\frac{\eta_w}{\eta_b} \right)^n \quad (67)$$

where η_w and η_b are the dynamic (absolute) viscosities at the tube wall and at the bulk flow temperature. The power index n depends on the Reynolds number and the heat flow direction (Fig. 14). For $Re > 10^3$, $n \approx 0$ and there is no appreciable effect of temperature difference on Eu . When $\eta_w > \eta_b$ (e.g., in cooling a liquid), the exponent n is given by

$$n = 0.776 \exp(-0.545 Re^{0.256}) \quad (68)$$

and when $\eta_w < \eta_b$ (e.g., in heating a liquid), n is given by

$$n = 0.968 \exp(-1.076 Re^{0.196}) \quad (69)$$

II. Effect of property variations through bank

An evaluation of the pressure drop must take into account the bulk temperature dependence of the fluid physical properties. For liquids, an arithmetic mean of the density may be chosen for the entrance and exit

conditions, the variation being low. When larger variations occur, the bank may be considered as a group of several smaller banks, each with a limited number of rows. Density values for each of the elementary banks are calculated from their average local temperatures. A subsequent summation yields the total value of pressure drop, which takes account of density variation. The effect of bulk temperature dependence of viscosity is evaluated similarly.

III. Accelerational pressure drop arising from temperature rise

Nonisothermal gaseous flows in banks undergo variations of density and velocity. Acceleration involves

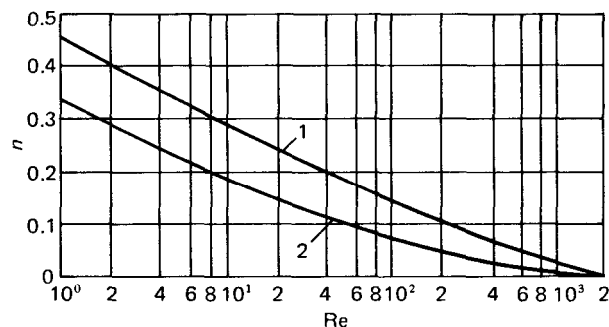


Figure 14. The value of n , the power index of η_w/η_b , as a function of Re . (1) Cooling. (2) Heating.

additional pressure drop, which may be described for a constant channel cross section by

$$Ap_r = \rho_2 u_2^2 - \rho_1 u_1^2 = \frac{T_2 - T_1}{T_m'} \rho_m u_m^2 \quad (70)$$

where Δp_a is the pressure drop due to acceleration, $T_{1,p}$, u_1 and T_2 , ρ_2 , u_2 are the gas temperatures, density, and velocity in the inlet section and in the outlet section, respectively. $T_m' = 273.15 + T_m$, T_m is the mean temperature in the bank, ρ_m is the density of the gas at T_m , and u_m is the mean velocity, referred to T_m . The value of Ap_r is positive in heating and negative in cooling.

IV. Net gravitational pressure drop due to density difference

In addition to the frictional and accelerational pressure drops, there is a gravitational pressure drop $\rho g H \sin \theta$, where ρ is the mean density in the bundle, H is the height, g is the acceleration due to gravity, and θ is the angle of inclination of the flow to the horizontal. If the bundle is surrounded by and connected to fluid of density ρ_0 , there is a net driving pressure drop (draft) given by

$$\Delta p_d = (\rho_0 - \rho) g H \sin \theta \quad (71)$$

This pressure drop should be added to the frictional and accelerational pressure drops to give the total pressure drop. Note that in natural draft systems the total pressure drop is zero.

(d) Pressure drop of yawed banks of tubes

For banks that are yawed with respect to the flow direction by an angle ψ (see Fig. 15), the Euler number Eu_ψ is related to the Euler number for pure cross flow Eu by a yaw factor k_ψ :

$$Eu_\psi = k_\psi Eu \quad (72)$$

Curves for k_ψ are given in Fig. 15 for staggered and in-line banks, respectively, for the ranges of Re from 10^4 to 2×10^5 . These curves are fitted by the equations

$$k_\psi = 1.245 \exp(-0.478\psi^{-1.733}) \quad (73)$$

for staggered banks and

$$k_\psi = 1.107 \exp(-0.301\psi^{-2.412}) \quad (74)$$

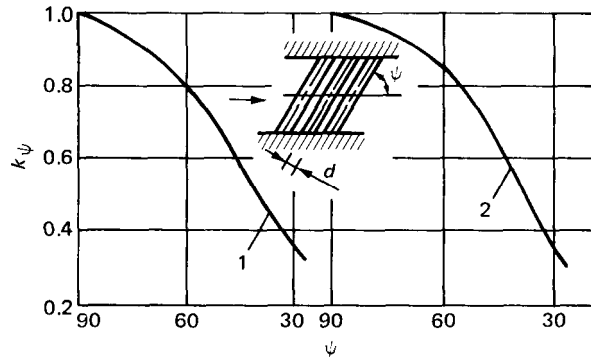


Figure 15 The value of yaw factor k as a function of yaw angle ψ . (1) For staggered banks. (2) For in-line banks with a from 1.26 to 2.0 and $b = 2.0$.

for in-line banks, where ψ is in radians. Further information on yaw effects for banks of either circular or elliptic tubes is given in [11].

(e) Summary of calculation procedure for pressure drop

To calculate the pressure drop in a bank of z rows of tubes, the following procedure is adopted based on the recommendations given earlier.

1. Estimate the mean bulk fluid physical properties at the arithmetic mean of the inlet and outlet temperatures.
2. Calculate the maximum intertube velocity u using Eqs. (4)-(6).
3. Calculate the Reynolds number, $Re = ud/\nu$.
4. Calculate the value of Eu/k_1 for an infinite bank using Eqs. (33)-(39) for in-line banks or Eqs. (44)-(54) for staggered banks.
5. Calculate the value of k_1 from Eqs. (40)-(43) (in-line banks) or Eqs. (53)-(57) (staggered banks) and calculate Eu from $Eu = (Eu/k_1)k_1$. Interpolate the values of k_1 logarithmically for the appropriate value of Reynolds number.
6. Calculate the value of Euler number for z rows, $Eu_z = C_z Eu$, interpolating Table 1 logarithmically in terms of Reynolds number for C_z . Alternatively, C_z may be calculated via Eqs. (58)-(66) for C_z and taking $C_z = (1/z) \sum_{i=1}^z C_i$.
7. Correct for wall-to-bulk temperature viscosity variation via Eq. (67), calculating the exponent n from Eq. (68) (cooling) or Eq. (69) (heating).
8. Check effects of large-scale bulk property variations, acceleration, and net gravitational pressure drop [see Sec. B(c)].
9. Correct for the effect of yaw using Eq. (72), with k_ψ calculated from Eq. (73) or (74).

C. Pressure drop in banks of finned and rough-surfaced tubes

(a) Pressure drop in banks of finned tubes

Pressure drop in banks of finned tubes is a function of the tube geometric parameters as illustrated in Fig. 2. The velocity profiles and boundary-layer thicknesses around the tubes are determined by the parameters illustrated and, of course, by fluid properties and velocity. Significant differences are noted between fluid flows on the first-row tubes and those in the inner rows. A high degree of turbulence exists inside the bank, in the intertube and interfin spaces. In the first two rows, separation of the boundary layer at $\phi \approx 90^\circ$ (see Fig. 1) is followed by a circulation zone. Effects of the turbulence on boundary-layer separation are observed from the third or fourth row onward. Comparisons with tubes in the first and the second rows suggests that the separation point for an inner tube is shifted downstream, and that the circulation zone is smaller in volume and more complex in structure. The lower the fin height h and the longer the fin spacing, the more is the flow on a finned tube similar to that on a plain tube. Conversely, the higher and closer the fins, the more the flow is similar to that in a slot.

Pressure drop over a finned-tube bank is a function of flow velocity, bank geometry, fin geometry, and fluid physical properties:

$$\Delta p = f(u, d, s, h, \delta_1, \delta_2, s_1, s_2, z, \eta, \rho) \quad (75)$$

Fin thickness is often found to have no significant effect on the pressure drop, and a simplified dimensionless form of Eq. 2.2.4(75) may be written:

$$Eu = 2 \frac{\Delta p}{\rho u^2 z} = f\left(\text{Re}, \frac{h}{d}, \frac{s}{d}, \frac{s_1}{d}, \frac{s_2}{d}, z\right) \quad (76)$$

In what follows, the correlations of Yudin and Tokhtarova [12] are stated and recommended. Alternative correlations are available in the literature [e.g., Jameison (13)], but it is beyond the scope of this present short section to give details of these.

I. Correlation for staggered banks of tubes with annular (ring-shaped) fiis

The correlation of Yudin and Tokhtarova [12] for this case is as follows:

For $2.2 \times 10^3 < \text{Re}_d^* < 1.8 \times 10^5$:

$$Eu = 2 \frac{\Delta p}{\rho u^2 z} = 5.4 \left(\frac{d^*}{d_e}\right)^{0.3} \text{Re}_d^{*-0.25} C_z \quad (77)$$

For $\text{Re}_d^* > 1.8 \times 10^5$:

$$Eu = 0.26 \left(\frac{d^*}{d_e}\right)^{0.3} C_z \quad (78)$$

where d^* is a relative diameter given by

$$d^* = \frac{dA_{\text{tube}}}{A_{\text{total}}} + \frac{A_{\text{fin}}}{A_{\text{total}}} \sqrt{0.785(D^2 - d^2)} \quad (79)$$

where d is the base tube diameter, D is the fin diameter (see Fig. 2), A_{tube} is the bare tube surface area per unit tube length ($= \pi d$), A_{fin} is the fin surface area per unit length, and A_{total} is the total surface area per unit length. The hydraulic mean diameter d_e is given by

$$d_e = \frac{4 \times \text{flow area}}{\text{flow perimeter}} = \frac{2[s(s_1 - d) - 2\delta h]}{2h + s} \quad (80)$$

(refer to Fig. 2 for definitions of s, s_1, h , and F). The Reynolds number Re_d^* is defined as ud^*/ν , where u is the maximum intertube velocity calculated for plain tube banks of tubes with diameter d and spacings s_1 and s_2 from Eq. (4) or (5).

In Eqs. (77) and (78), the correction factor C_z takes account of the number of rows of tubes in the bundle and is given by $C_z = (1/z) \sum_{z=1}^z c_z$, where c_z is the factor by which the pressure drop over the z th row differs from the average pressure drop per row in an infinite bundle. The variation of c_z with z is illustrated in Fig. 16 and is given by

$$c_z = 0.934 + \frac{0.355}{z - 0.667} \quad c_z = 1, z \geq 6 \quad (81)$$

The appropriate values of C_z and c_z are also given in Table 2.

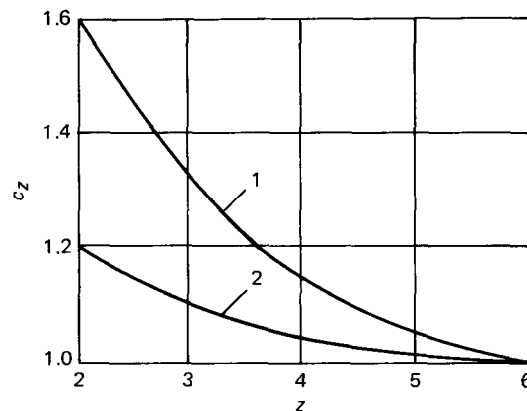


Figure 16 Factor for the number of rows of finned tubes. (1) In-line bank. (2) Staggered bank.

Table 2 Correction factor for row-to-row variations for staggered banks of annular fins

No. of rows	1	2	3	4	5	6	7	8	9	10
c_z	2.000	1.200	1.086	1.040	1.016	1.000	1.000	1.000	1.000	1.000
C_z	2.000	1.600	1.429	1.332	1.268	1.224	1.192	1.168	1.149	1.134

II. Correlation for in-line banks of tubes with annular (ring-shaped) and square fins

The Yudin and Tokhtarova [12] correlation for in-line banks of annular and square-shaped fins is as follows:

$$Eu = 0.52 \left(\frac{d^*}{d_e} \right)^{0.3} \left(\frac{b-1}{a-1} \right)^{0.68} Re_{d^*}^{-0.08} C_z \quad (82)$$

where d_e is defined from Eq. (80), $a = s_1/d$, $b = s_2/d$ (see Fig. 2), $Re_{d^*} = ud^*/\nu$, and d^* is given by

$$d^* = \frac{A_{\text{tube}} d}{A_{\text{total}}} + \frac{A_{\text{fin}}}{A_{\text{total}}} \sqrt{\frac{A'_{\text{fin}}}{2n_{\text{fin}}}} \quad (83)$$

where A_{tube} is the bare tube surface area per unit tube length ($= \pi d$), A_{fin} is the fin surface area per unit length, A_{total} is the total surface area per unit length, A'_{fin} is the fin-side surface area, and n_{fin} is the number of fins per unit length. Equation (82) applies over the ranges $4 \times 10^3 < Re_{d^*} < 1.6 \times 10^5$ with $0.85 < d^*/d_e < 11.5$ and $0.5 < (b-1)/(a-1) < 2$.

The value of $C_z = (1/z) \sum_{z=1}^z c_z$ is calculated using the relationship

$$c_z = 0.738 + \frac{1.509}{z - 0.250} \quad c_z = 1, z > 6 \quad (84)$$

where C_z is the correction coefficient to Eq. (82) for the pressure drop across the z th tube row. Values of C_z and c_z calculated from Eq. (84) are given in Table 3.

III. Correlation for staggered banks of tubes with helical fins

For multirow (i.e., $z > 6$) banks of staggered tubes with helical fins, Stasiulevičius and Skrinska recommend the following correlation.

For $10^4 < Re < 10^5$:

$$Eu = \frac{13.10(1 - s/d)^{1.8} Re^{-0.25}}{a^{0.55} b^{0.5} (1 - h/d)^{1.4}} \quad (85)$$

For $10^5 < Re < 10^6$:

$$Eu = \frac{0.74(1 - s/d)^{1.8}}{a^{0.55} b^{0.5} (1 - h/d)^{1.4}} \quad (86)$$

where $Re = ud/\nu$ and the other parameters are defined in Fig. 2. Equations (85) and (86) apply over the ranges $2.2 < a < 4.13$, $1.27 < b < 2.14$, $0.12 < s/d < 0.28$, $0.12 < h/d < 0.59$, helix angle $2-4^\circ$, and with $\delta_2/\delta_1 = 2$.

(b) Pressure drop for banks of rough-surfaced tubes

Tube surface roughness may increase the momentum transfer in the vicinity of the wall. In turbulent flows, tube roughness increases resistance when the elements of the roughness are higher than the viscous sublayer, that is, when k^+ (the dimensionless height of the roughness elements) is greater than 5. Here, $k^+ = u^*k/\nu$, where k is the actual height of the elements, u^* is the friction velocity (given by $\sqrt{\tau_w/\rho}$, where τ_w is the wall shear stress and ρ is the fluid density), and ν is the kinematic viscosity. At $k^+ > 70$, the roughness effect is dominant, and the shear stress at the wall is determined by the form drag of separate elements of roughness. The effect of roughness on Euler number for staggered banks is illustrated in Fig. 18, where Eu_r is the Euler number for rough tubes and Eu is the value for plain tubes. For each relative roughness value (k/d), the effect of roughness begins to be important above a given value of Reynolds number (this is similar to the situation for flow in tubes). The curves in Fig. 18 are represented by the following equations.

For $k/d = 10^{-3}$, $2 \times 10^5 < Re < 10^6$:

Table 3 Correction factors for row-to-row variations for in-line banks of annular (ring-shaped) or square fins

No. of rows	1	2	3	4	5	6	7	8	9	10
c_z	2.750	1.600	1.287	1.140	1.056	1.000	1.000	1.000	1.000	1.000
C_z	2.750	2.175	1.879	1.694	1.567	1.472	1.405	1.354	1.315	1.283

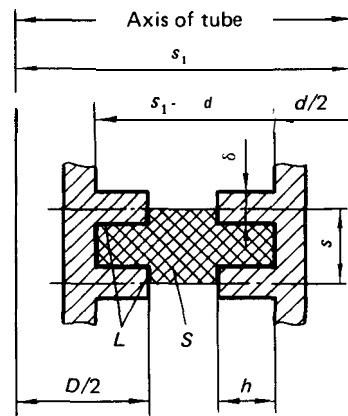


Figure 17 Determination of the equivalent diameter.

$$\frac{Eu_r}{Eu} = 2.013 \exp(-189.29 Re^{-0.459}) \quad (87)$$

For $k/d = 5 \times 10^{-3}$, $2 \times 10^4 < Re < 10^6$:

$$\frac{Eu_r}{Eu} = 2.185 \exp(-90.477 Re^{-0.458}) \quad (88)$$

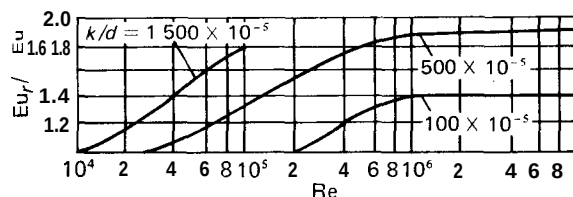
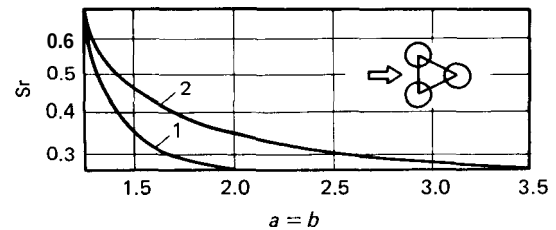
For $k/d = 15 \times 10^{-3}$, $10^4 < Re < 10^5$:

$$\frac{Eu_r}{Eu} = 1.115 \times 10^{-4} \exp(-7.12 Re^{0.0266}) \quad (89)$$

For in-line banks, the effects of roughness is somewhat less than in staggered banks.

D. Hydrodynamic parameters of separated flows in banks of tubes

When a fluid flows in a cross flow over a tube, vortices are shed from the downstream side. The frequency f of vortex shedding is characterized by the Strouhal number, $Sr = fd/u$, where d is the tube diameter and u is the fluid velocity. In tube banks [where u is normally defined from Eqs. (4) and (5)], the pattern of vortex shedding is complex and gives rise, in some geometries, to much higher values of Sr than for single tubes. An analysis of the results for Sr for a wide range of Re , a , and b for in-line and staggered banks suggests that there is usually no significant effect of Re on Sr . However, results obtained by the present

Figure 18 The value of ratio Eu_r/Eu versus Re number for different roughness parameters k/d for a staggered bank, 2.0×2.0 , inner row.Figure 19 Strouhal number as a function of a for symmetric staggered banks. Curve 1, first row. Curve 2, inner row.

authors for staggered banks with the relative longitudinal pitch $b = 2.5$ indicate that Sr decreases by 50% with increasing Re .

Figures 19 and 20 present values of Sr obtained by the present authors and others [14,15] for symmetric in-line ($a = b$) and staggered ($s_1 = s_2$) banks with a in the range 1.25-3.5. They suggest that Sr decreases with increasing a (or b) and approaches a constant value at high values of a . The following relationships fit the curves shown in Figs. 19 and 20.

For the first row of symmetric ($s_1 = s_2$) staggered banks, for $1.25 < a < 2.0$ and $Re < 1.5 \times 10^3$,

$$Sr = 0.195 + \frac{0.0576}{a - 1.116} \quad (90)$$

For the inner rows of symmetric ($s_1 = s_2$) staggered banks, for $1.25 < a < 2.0$ and $Re < 1.5 \times 10^3$,

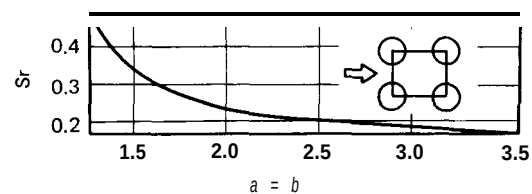
$$Sr = 0.21 + \frac{0.154}{a - 0.913} \quad (91)$$

For symmetric ($a = b$) in-line banks, for the first and inner rows, and for $1.25 < a < 3.5$,

$$Sr = 0.138 + \frac{0.0939}{a - 0.987} \quad (92)$$

For any given value of a , the value of Sr is highly affected by changes of the longitudinal pitch. The value of Sr increases sharply with decreasing b .

The difference of the front and rear pressures on a tube gives rise to a constant force directed downstream. Another force is generated by vortex shedding, fluctuating in the longitudinal and in the transverse direction alternatively, and causing the tube to vibrate in the **same** manner. The amplitude F_y of the fluctuating force, transverse to the flow direction, on **tube**

Figure 20 Strouhal number as a function of a for symmetric in-line banks.

length L may be expressed in terms of the lift coefficient c_L ,

$$c_L = \frac{2F_y}{\rho u^2 A_p} \quad (93)$$

where A , is the cross-sectional area of a tube parallel to the flow direction ($A_p = Ld$). Values of c_L for in-line banks are given by Chen [15] for the Reynolds number range 1.36×10^3 to 2.66×10^4 and are shown in Fig. 21. Local turbulence also generates pressure fluctuations of a wide spectrum of frequencies, and those approaching the natural frequency f_n of the tube itself are amplified. The volume of fluid in the inter-tube space also oscillates with its own acoustic frequency f_a , in the transverse direction.

The frequency of vortex shedding is determined from Sr and is compared with the natural frequency of the tubes, f_n , and with the fluid acoustic frequency, f_a . By avoiding similar values of the frequencies involved, resonance vibrations can be excluded. Resonance vibration is found possible with $1/3 < f/f_n < 3$ and un-

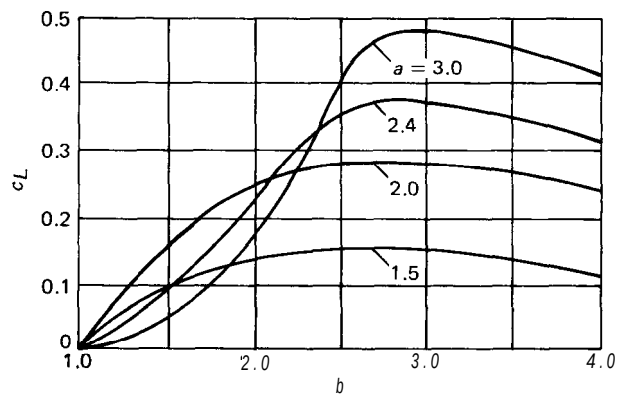


Figure 21 Lift coefficient versus longitudinal pitch b , for in-line banks, for different transverse pitches a .

avoidable with $0.75 < f/f_n < 1.25$. Acoustic resonance is possible with $1/2 < f/f_a < 2$ and unavoidable with $0.75 < f/f_a < 1.25$. Resonance implies much noise and additional load on the tubes and the shell. More information is given by Blevins [16] and also in Sec. 4.6.

NOMENCLATURE FOR SECTION 2.2.4

a	relative transverse pitch, s_1/d	S	cross-sectional area, m^2
b	relative longitudinal pitch, s_2/d	Sr	Strouhal number, fd/u
c_f	skin friction coefficient, $2\tau_w/\rho u^2$	T, T'	temperature, $^{\circ}C, K$
c_D	drag coefficient, $2F_x/\rho u^2 Ld$	u_b	main flow velocity [Fig. (1)], m/s
c_L	lift coefficient, $2F_y/\rho u^2 Ld$	u	mean velocity in the minimum intertube space, m/s
d	diameter of tube, m	x	linear distance from front stagnation point, m
Eu	Euler number, $2\Delta p/\rho u^2$	y	distance normal to the wall, m
f	friction factor, $Eu/4$	z	number of tube rows in a bank
H	height, m	Δp	pressure drop, Pa
k_2	geometric constant, Eq. (27)	η	dynamic (absolute) viscosity, $kg/m \cdot s$
L	length, m	ν	kinematic viscosity, m^2/s
$\dot{M}$	mass flow rate, kg/s	ρ	density, kg/m^3
$\dot{m}$	mass velocity (mass flow per unit area), $kg/m^2 \cdot s$	τ	shear stress, Pa
p_b	main flow pressure, [Eq. (1)], Pa	ϕ	angular distance from the front stagnation point, deg
p_x	local pressure, Pa		
P	pressure coefficient [Eq. (3)]		
Pr	Prandtl number, $\eta c_p/\lambda$		
r	power index of Re [Eq. (27)]		
Re	Reynolds number, ud/ν		
s_1	transverse pitch of a bank of tubes, [Fig. (1)], m		
s_2	longitudinal pitch of a bank of tubes [Fig. (1)], m		
s'_2	diagonal pitch of a staggered bank [Fig. (1)], m		
		Subscripts	
		b	conditions in the main flow
		w	conditions on the wall
		m	mean value
		x	local conditions

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5.5.4

Constants for binary mixtures

R. N. Maddox

■ This section supplies the constants necessary for prediction of **nonideal** behavior using the Analytical Solution Of Groups (Table 1), UNIFAC (Table 2) and

Parameters From Group Contributions (Table 3). Methods discussed in Section 5.2.2B.

Table 1a Parameters for use in the analytical solution of groups

Alcohol-hydrocarbon-water systems at 60°C (1)				
Group pair	Compounds	Assignments		
		CH ₂	OH	FH
CH ₂ OH	Hexane	6.0		6.0
	Water		1.4	1.0
	Water		1.4	1.0
	Pentane	5.0		5.0
	Methanol	1.0	1.0	2.0
	Water		1.4	1.0
	Heptane	7.0		7.0
	Butanol	4.0	1.0	5.0
Parameters				
CH ₂ OH		1.0	0.305	
		0.0147	1 . 0	

Table 1b Parameters for use in the analytical solution of groups

Methanol-glycerol systems (1)					
Group pair	Compounds	Assignments			
		CH ₂	OH	GOH	FH
CH₂ - Glycerol	Glycerol			6.0 6.0	6.0 6.0
OH - Glycerol	Methanol	1.0	1.0		2.0
Calc.	Water		1.4		1.0
	Glycerol			6.0	6.0
Parameters					
CH₂		1.0	0.305	0.353	
OH		0.0147	1.0	1.095	
Glycerol		0.0153	0.991	1.0	

Table 1c Parameters for use in the analytical solution of groups

Ketone-alcohol-water systems at 60°C (1)					
Group pair	Compounds	Assignments			
		CH ₂	OH	C=O	FH
CH₂	Heptane	7.0			7.0
C=O	Acetone	2.0		1.0	3.0
OH -	Methanol	1.0	1.0		2.0
c - o	MEK	3.0		1.0	4.0
	Water	0	1.4		1.0
Parameters					
CH₂		1.0	0.305	1.333	
OH		0.0147	1.0	0.668	
c - o		0.0503	0.840	1.0	

Table 1d parameters for use in the analytical solution of groups

Ether-alcohol-water systems at 60° C (1)					
Group pair	Compounds	Assignments			
		CH ₂	OH	-O-	FH
CH₂ -0	Heptane	7.0			7.0
	Diethyl ether	4.0		1.0	5.0
CH-OH	Diethyl ether	4.0		1.0	5.0
OH-O	Ethanol	2.0	1.0		3.0
	Water		1.4		1.0
Calc.	Dioxane	4.0		2.0	6.0
	Methylal	3.0		2.0	5.0
	Methanol	1.0	1.0		2.0
Parameters					
CH₂		1.0	0.305	1.711	
OH		0.0147	1.0	0.355	
-O-		0.341	1.03	1.0	

Table 1e Parameters for use in the analytical solution of groups

Aqueous nitrile systems at 75°C (1)						
Group pair	Compounds	Assignments				
		CH ₂	CH	CN	OH	FH
CH-CN	Acetonitrile	1.0		1.0		3.0
	Acrylonitrile	1.0	1.0	1.0		4.0
CN-OH	Acetonitrile					
	Water				1.4	1.0
Parameters						
CH₂		1.0	0.825	0.4455	0.315	
CH		1.17	1.0	0.0338	0.680	
CN		0.047	0.385	1.0	0.291	
OH		0.021	0.025	0.549	1.0	

Table 1f Parameters for use in the analytical solution of groups

Ester-alcohol systems at 50°C (1)						
Group pair	Compounds	Assignments				
		CH₂	COO	OH	FH	
CH ₂ -COO	Propylformate	3.0	3.0			6.0
	Hexane	6.0				6.0
	Decane	10.0				10.0
COO-OH	Ethylpropionate	5.0	3.0			8.0
	Methylacetate	2.0	3.0			5.0
	Methanol	1.0		1.0		2.0
Parameters						
CH₂		1.0	0.072	0.305		
c o o		1.096	1.0	1.1179		
OH		0.0147	0.165	1.0		

Table 1g parameters for use in the analytical solution of groups

Aromatic-alcohol systems at 80° C (1)						
Group pair	Compounds	Assignments				
		CH ₂	CA	OH	FH	
CH ₂ -CA	Heptane	7.0				7.0
	Benzene		6.0			6.0
CA-OH	Ethanol	2.0		1.0		3.0
	Benzene		6.0			6.0
Calc.	Toluene	1.0	6.0			7.0
	Isoamyl alcohol	5.0		1.0		6.0
Parameters						
CH₂		1.0	0.734	0.32		
CA		1.24	1.0	0.534		
OH		0.0245	0.045	1.0		

Table 1h Parameters for use in the analytical solution of groups

Chloride systems (1)						
Group pair	Compounds	Assignments				
		CH ₂	OH	Cl	HBH	FH
CH ₂ -Cl	Cyclohexane	4.0	1.0			4.0
	CCl ₄	1.0		4.0		5.0
OH-Cl	Methanol	1.0	1.0			2.0
	CCl ₄	1.0		4.0		5.0
OH-HBH	Methanol	1.0	1.0			2.0
	Chloroform	1.0		3.0	1.0	4.0
	Ethanol	2.0	1.0			3.0
Parameters						
CH ₂		1.0	0.29	0.837	1.0	
OH		0.007	1.0	0.0112	0.0722	
Cl		1.128	0.591	1.0	1.0	
HBH		1.0	5.077	1.0	1.0	

Table 1i Parameters for use in the analytical solution of groups

Fluorocompounds (1)						
Group pair	Compounds	Assignments				FH
		CH ₂	CF ₂	0	HBH	
CH ₂ -O	Cyclohexane	6.0				4.0
	Dioxane	4.0		2.0		4.65
CH ₂ -CF	Hexane	6.0				6.0
	Perfluorohexane		18.0			9.8
CF ₂ -O	Perfluoroheptane		12.0			11.4
	Dioxane					
HBH-0	HPDFH		21.0			11.4
	Dioxide	4.0		2.0		4.65
Parameters						
		CH ₂	CF ₂	0	HBH	
CH ₂		1.0	0.424	0.00153	1.0	
CF ₂		1.541	1.0	0.604	1.0	
0		0.495	0.334	1.0	0.0015	
HBH		1.0	1.0	3.126	1.0	

Table 1j Parameters for use in the analytical solution of groups

Aromatic-ketone mixtures (1)						
Group pair	Compounds	Temp., °C	Assignments			
			CH,	CA	C=O	FH
CH ₂ c = o	Heptane	1	7.0			7.0
		60				
	Acetone	25	2.0		1.0	3.0
CH–		60				
	Heptane	25	7.0			
		60				
CA–	Benzene	25		6.0		6.0
		60				
	Benzene	25		6.0		6.0
C=O		60				
	Acetone	25	2.0		1.0	3.0
		60				
Calc.	Xylene	60	2.0	6.0		8.0
	Diisobutyl ketone	60	8.0		1.0	9.0
Parameters						
CH ₂		25	1.0	0.705	0.899	
		60	1.0	0.709	1.33	
		150	1.0	0.66	2.10	
CA		25	1.24	1.0	1.418	
		60	1.266	1.0	1.578	
		150	1.52	1.0	1.9	
c = o		25	0.0480	0.144	1.0	
		60	0.0503	0.162	1.0	
		150	0.075	0.21	1.0	

Table 1k Parameters for use in the analytical solution of groups

Anhydride-carboxylic acid mixtures (2)						
Compound	Sizegroups	Assignments				
		CH, OH	Benzene	Acid	Anhydride	
Acetic acid	2	1		1		
Acetic anhydride	4	2			1	
Benzene	6		6			
Benzoic acid	7		6	1		
n-Butanol	5	4	1			
o-Cresol	8	1	1	6		
Cyclohexane	6	6				
Ethanol	3	2	1			
Ethylbenzene	8	2	6			
Formic acid	2			1		
*Octane	8	8				
Phenol	7		1	6		
Phthalic acid	8		6	2		
Phthalic anhydride	8		6		1	
Propionic acid	3	2	1			
Toluene	7	1	6			
o-Toluic acid	8	1	6	1		
Water	1		1.4			
Parameters						
		-CH ₂	-OH	Benzene (=CH-)	Acid (-COOH)	Anhydride (-OCOO-)
CH₂		1.0	0.305	0.734	1.1333	0.7703
OH		0.0147	1.0	0.045	0.1960	
Benzene		1.24	0.534	1.0	1.1372	0.9841
Acid		0.0340	2.3518	0.0442	1.0	0.6205
Anhydride		0.0249		0.1876	0.5369	1.0

Table 2a Parameters for use with UNIFAC

Group name	R_k	Q_k	Sample group assignment
CH₂			
CH₃	0.9011	0.848	Butane: 2 CH ₂ , 2 CH ₃
CH₂	0.6744	0.540	
CH	0.4469	0.228	i-Butane: 3 CH ₂ , 1 CH
C	0.2 195	0.000	2,2-Dimethylpropane 4 CH ₃ , 1 C
C=C			
CH ₂ =CH	1.3454	1.176	1-Hexene : 1 CH ₂ , 3 CH ₂ , 1 CH ₃ , =CH ₂
CH=CH	1.1167	0.867	2-Hexene : 2 CH ₂ , 2 CH ₂ , 1 CH=CH
CH=C	0.8886	0.676	2-Methylbutene-2: 3 CH ₂ , 1 CH=C
CH ₂ =C	1.1173	0.988	2-Methylbutene-1 : 2 CH ₂ , 1 CH ₃ , 1 CH ₂ , =C
ACH			
ACH	0.5313	0.400	Benzene: 6 ACH
AC	0.3652	0.120	Styrene: 1 CH ₂ =CH, 5 ACH, 1 AC
ACCH,			
ACCH,	1.2663	0.968	Toluene: 5 ACH, 1 ACCH,
ACCH,	1.0396	0.660	Ethylbenzene: 1 CH ₂ , 5 ACH, 1 ACCH,
ACCH	0.8121	0.348	Cumene: 2 CH ₂ , 5 ACH, 1 ACCH

Table 2a Parameters for use with UNIFAC (Continued)

Group name	R_k	Q_k	Sample group assignment
CCOH			
CH ₂ CH ₂ OH	1.8788	1.664	1-Propanol: 1 CH, , 1 CH, CH, OH
CHOHCH,	1.8780	1.660	2-Butanol : 1 CH, , 1 CH, , 1 CHOHCH,
CHOHCH,	1.65 13	1.352	3-Octanol : 2 CH,, 4 CH, , 1 CHOHCH,
CH ₃ CH ₂ OH	2.1055	1.972	Ethanol: 1 CH, CH, OH
CHCH, OH	1.6513	1.352	Isobutanol: 2 CH, , 1 CHCH, OH
CH, OH	1.4311	1.432	Methanol: 1 CH, OH
H ₂ O	0.92	1.40	Water: 1 H ₂ O
ACOH	0.8952	0.680	Phenol: 5 ACH, 1 ACOH
CH ₂ CO			
CH, CO	1.6724	1.488	Ketone group is 2nd carbon; 2-Butanone : 1 CH, , 1 CH, , 1 CH, CO
CH, CO	1.4457	1.180	Ketone group is any other carbon; 3-Pentanone : 2 CH, , 1 CH, , 1 CH, CO
CHO	0.9980	0.948	Acetaldehyde: 1 CH, , 1 CHO
COOC			
CH ₃ COO	1.9031	1.728	Butyl acetate: 1 CH, , 3 CH, , 1 CH ₃ COO
CH, COO	1.6764	1.420	Butyl propanoate: 2 CH, , 3 CH, , 1 CH ₂ COO
CH ₂ O			
CH, O	1.1450	1.088	Dimethyl ether: 1 CH, , 1 CH, O
CH ₂ O	0.9183	0.780	Diethyl ether: 2 CH,, 1 CH, , 1 CH, O
CH-O	0.6908	0.468	Diisopropyl ether: 4 CH, , 1 CH, 1 CH-O
FCH, O	0.9183	(1.1)	Tetrahydrofuran : 3 CH, , 1 FCH, O
CNH,			
CH, NH,	1.5959	1.544	Methylamine: 1 CH, NH,
CH, NH,	1.3692	1.236	n-Propylamine: 1 CH, , 1 CH₂ , 1 CH₂NH₂ ,
CHNH,	1.1417	0.924	Isopropylamine: 2 CH, , 1 CHNH,
CNH			
CH, NH	1.4337	1.244	Dimethylamine: 1 CH, , 1 CH, NH
CH, NH	1.2070	0.936	Diethylamine: 2 CH, , 1 CH, , 1 CH, NH
CHNH	0.9795	0.624	Diisopropylamine: 4 CH, , 1 CH, 1 CHNH
ACNH,	1.0600	0.816	Aniline: 5 ACH, , 1 ACNH,
CCN			
CH, CN	1.8701	1.724	Acetonitrile : 1 CH, CN
CH, CN	1.6434	1.416	Propionitrile: 1 CH, , 1 CH, CN
COOH			
COOH	1.3013	1.224	Acetic acid: 1 CH, , 1 COOH
HCOOH	1.5280	1.532	Formic acid: 1 HCOOH
cc1			
CH ₂ Cl	1.4654	1.264	Butylchloride: 1 CH, , 2 CH, , 1 CH, Cl
CHCl	1.2380	0.952	Isopropyl chloride: 2 CH, , 1 CHCl
cc1	1.0106	0.724	tert-Butyl chloride: 3 CH, , 1 CC1
CCl ₂			
CH ₂ Cl ₂	2.2564	1.988	Dichloromethane: 1 CH, Cl,
CHCl ₂	2.0606	1.684	1,1-Dichloroethane: 1 CH, , 1 CHCl₂
CCl ₂	1.8016	1.448	2,2-Dichloropropane: 2 CH, , 1 CCl₂
CCl ₃			
CHCl ₃	2.8700	2.410	Chloroform: 1 CHCl₃
CCl ₃	2.6401	2.184	1,1,1-Trichloroethane : 1 CH ₃ , 1 CCl₃
CCl ₄	3.3900	2.910	Carbon tetrachloride: 1 CCl₄
ACCl	1.1562	0.844	Chlorobenzene: 5 ACH, 1 ACCl
CNO,			
CH, NO,	2.0086	1.868	Nitromethane: 1 CH, NO,
CH, NO,	1.7818	1.560	1-Nitropropane : 1 CH, , 1 CH, , 1 CH, NO,
CHNO,	1.5544	1.248	2-Nitropropane : 2 CH, , 1 CHNO,
ACNO,	1.4199	1.104	Nitrobenzene: 5 ACH, 1 ACNO,
CS ₂	2.057	(1.65)	Carbon disulfide : 1 CS₂

Table 2b Interaction parameters^a

	CH ₂	C=C	ACH	ACCH ₂	CCOH	CH ₂ OH	H ₂ O	ACOH
CH ₂	0	— 200.0	61.13	76.50	737.5	697.2	1318	(2789)
C=C	2520	0	340.7	4102	(535.2)	(1509)	599.6	n.a.
ACH	— 11.12	— 94.78	0	167.0	477.0	637.4	903.8	(1397)
ACCH ₂	— 69.70	— 269.7	(— 146.8)	0	469.0	603.3	(5695)	(726.3)
CCOH	— 87.93	(121.5)	— 64.13	— 99.38	0	127.4	285.4	(257.3)
CH ₂ OH	16.51	(— 52.39)	— 50.00	— 44.50	— 80.78	0	— 181.0	n.a.
H ₂ O	580.6	511.7	362.3	(377.6)	— 148.5	289.6	0	442.0
ACOH	(311.0)	n.a.	(2043)	(6245)	(— 455.4)	n.a.	— 540.6	0
CH ₂ CO	26.76	— 82.92	140.1	365.8	129.2	108.7	605.6	n.a.
CHO	(505.7)	n.a.	n.a.	n.a.	n.a.	— 340.2	(— 155.7)	n.a.
COOC	114.8	n.a.	85.81	— 170.00	109.9	249.6	1135	853.6
CH ₂ O	83.36	76.44	52.13	65.69	42.00	(339.7)	634.2	n.a.
CNH ₂	— 30.48	(79.40)	— 44.85	n.a.	(— 217.2)	(— 481.7)	— 507.1	n.a.
CNH	65.33	— 41.32	— 22.31	(223.0)	— 243.3	(— 500.4)	— 547.7	h.a.
ACNH ₂	5339	n a	650.4	3399	(— 245.0)	n.a.	— 339.5	n.a.
CCN	35.76	26.09	(— 22.97)	— 138.4	n.a.	(168.8)	242.8	n.a.
COOH	315.3	(349.2)	62.32	268.2	— 17.59	1020	— 292.0	n.a.
CCl	(9 1.46)	(— 24.36)	(4.680)	(122.9)	368.6	529.0	698.2	n.a.
CCl ₂	(34.01)	(— 52.71)	n.a.	n.a.	601.6	(669.9)	708.7	n.a.
CCl ₃	36.70	(— 185.1)	288.5	(33.61)	491.1	649.1	826.8	n.a.
CCl ₄	— 78.45	(— 293.7)	— 4700	134.7	570.7	860.1	1201	(1616)
ACCl	— 141.3	n.a.	(— 237.7)	n.a.	(134.1)	n.a.	920.4	n.a.
CNO ₂	— 32.69	(— 49.92)	10.38	— 97.05	n.a.	(252.6)	614.2	n.a.
ACNO ₂	(5541)	n.a.	(1825)	n.a.	n a	n.a.	360.7	n.a.
CS ₂	(11.46)	n.a.	— 18.99	n.a.	442.8	914.2	1081	n.a.
	CH ₂ CO	CHO	COOC	CH ₂ O	CNH ₂	CNH	ACNH ₂	CCN
CH ₂	476.4	(677.0)	232.1	251.5	391.5	255.7	1245	612.0
C=C	524.5	n.a.	n.a.	289.3	(396.0)	273.6	n.a.	370.9
ACH	25.77	n.a.	5.994	32.14	161.7	122.8	668.2	(212.5)
ACCH ₂	— 52.10	n.a.	5688	213.1	n.a.	(— 49.29)	612.5	6096
CCOH	48.16	n.a.	76.20	70.00	(110.8)	188.3	(412.0)	n.a.
CH ₂ OH	23.39	306.4	— 10.72	(— 180.6)	(359.3)	(266.0)	n.a.	(45.54)
H ₂ O	— 280.8	(649.1)	— 455.4	— 400.6	357.5	287.0	213.0	112.6
ACOH	n.a.	n.a.	— 713.2	n.a.	n.a.	n.a.	n.a.	n.a.
CH ₂ CO	0	— 37.36	— 213.7	(5.202)	n.a.	n.a.	n.a.	428.5
CHO	128.0	0	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
COOC	372.2	n.a.	0	— 235.7	n.a.	(— 73.50)	n.a.	533.6
CH ₂ O	(52.38)	n.a.	461.3	0	n.a.	(141.7)	n.a.	n.a.
CNH ₂	n.a.	n.a.	n.a.	n.a.	0	(63.72)	n.a.	n.a.
CNH	n.a.	n.a.	(136.0)	(— 49.30)	(108.8)	0	n.a.	n.a.
ACNH ₂	n.a.	n.a.	n.a.	n.a.	n.a.	0	0	n.a.
CCN	— 275.1	n.a.	— 297.3	n.a.	n.a.	n.a.	n.a.	0
COOH	— 297.8	n.a.	— 256.3	— 338.5	n.a.	n.a.	n.a.	n.a.
cc1	(286.3)	n.a.	n.a.	225.4	n.a.	n.a.	n.a.	n.a.
CCl ₂	(423.2)	n.a.	(— 132.9)	(— 197.7)	n.a.	n.a.	n.a.	n.a.
CCl ₃	552.1	n.a.	176.5	— 20.93	n.a.	n.a.	n.a.	(74.04)
CCl ₄	372.0	n.a.	129.5	n a	n a	91.13	(1302)	(492.0)
ACCl	n.a.	n.a.	— 299.2	n.a.	203.5	— 108.4	n.a.	n.a.
CNO ₂	(— 142.6)	n.a.	n.a.	(— 94.49)	n a	n.a.	n.a.	n.a.
ACNO ₂	n a .	n a	n.a.	n.a.	n.a.	n.a.	(5250)	n.a.
CS ₂	298.7	n a	233.7	79.79	n.a.	n.a.	n.a.	n.a.

Table 2b Interaction parameters (Continued)

	COOH	cc1	CCl ₂	CCl ₃	CCl ₄	ACCl	CNO,	ACNO,	CS ₂
CH ₂	663.5	(35.93)	(53.76)	24.9	104.3	321.5	66 1.5	(543.0)	(114.1)
C≡C	(730.4)	(99.61)	(337.1)	(4583)	(5831)	n.a.	(542.1)	n.a.	n.a.
ACH	537.4	(- 18.8 1)	n.a.	- 231.9	3.000	(538.2)	168.1	(194.9)	97.53
ACCH,	603.8	(- 114.1)	n.a.	(- 12.14)	- 141.3	n.a.	3629	n.a.	n.a.
CCOH	77.61	- 38.23	- 185.9	- 170.9	- 98.66	(290.0)	n.a.	n.a.	73.52
CH, OH	- 289.5	- 38.32	(- 102.5)	- 139.4	- 67.80	n.a.	(75.14)	n.a.	- 31.09
H ₂ O	225.4	325.4	370.4	353.7	497.5	678.2	- 19.44	399.5	887.1
ACOH	n.a.	n.a.	n.a.	n.a.	(4894)	n.a.	n.a.	n.a.	n.a.
CH, CO	669.4	(- 191.7)	(- 284.0)	- 354.6	- 39.20	n.a.	(137.5)	n.a.	162.3
CHO	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
COOC	660.2	n.a.	(108.9)	- 209.7	54.47	808.7	n.a.	n.a.	162.7
CH ₂ O	664.6	301.1	(137.8)	- 154.3	n.a.	n.a.	(95.18)	n.a.	151.1
CNH,	n.a.	n.a.	n.a.	n.a.	n.a.	68.81	n.a.	n.a.	n.a.
CNH	n.a.	n.a.	n.a.	n.a.	71.23	(4350)	n.a.	n.a.	n.a.
ACNH,	n.a.	n.a.	n.a.	n.a.	(8455)	n.a.	n.a.	(- 62.73)	n.a.
CCN	n.a.	n.a.	n.a.	- 15.62	(- 54.86)	na	n.a.	n.a.	n.a.
COOH	0	44.42	- 183.4	n.a.	212.7	n.a.	n.a.	n.a.	n.a.
cc1	326.4	0	108.3	(249.2)	62.42	n.a.	n.a.	n.a.	n.a.
CCl ₂	1821	- 84.53	0	(0)	(56.33)	n.a.	n.a.	n.a.	n.a.
CCL,	n.a.	(- 157.1)	(0)	0	- 30.10	n.a.	n.a.	n.a.	256.5
CCl ₄	689.0	11.80	(17.97)	5 1.90	0	(475.8)	(490.9)	(534.7)	132.2
ACCl	n.a.	n.a.	n.a.	n.a.	(- 255.4)	0	(- 154.5)	n.a.	n.a.
CNO,	n.a.	n.a.	n.a.	n.a.	(- 34.68)	(794.4)	0	n.a.	n.a.
ACNO,	n.a.	n.a.	n.a.	n.a.	(5 14.6)	n.a.	n.a.	0	n.a.
CS ₂	n.a.	n.a.	n.a.	- 125.8	- 60.71	n.a.	n.a.	n.a.	0

^an.a., not available. Parameters in parentheses are based on limited data

Table 3 Summary of group contribution parameters for use with PFGC

Group	$E^{(0)}/R, ^\circ R$	$E^{(1)}/R, ^\circ R$	$b, \text{ft}^3/\text{lb-mole}$	s , degree of freedom per lattice site				
CH₄	- 410	- 7.5	0.325	1.75				
CH ₃ -	- 405	- 2.5	0.285	1.00				
-CH ₂ -	- 281	- 6.5	0.275	0.25				
- C L -	- 5	- 65	0.275	- 0.75				
$\begin{array}{c} \\ -\text{C}- \\ \end{array}$	580	- 80	0.265	- 2.25				
-OH	- 2880	- 1175	0.140	1.00				
-CHO O	- 1250	- 70	0.280	1.25				
$\begin{array}{c} \\ -\text{C}- \\ O \end{array}$	- 1259	- 245	0.290	0.50				
$\begin{array}{c} \\ -\text{C}-\text{O} \end{array}$	- 860	- 250	0.420	0.75				
CO ₂	- 799.1	- 151	0.270	2.00				
H ₂ S	- 931.5	- 106	0.295	2.00				
H ₂ O	- 2150	- 1500	0.192	1.25				
<i>a_{ij}'s</i>								
Group	CH ₄	$\begin{array}{c} \\ -\text{CH}- \\ \end{array}$	$\begin{array}{c} \\ -\text{C}- \\ \end{array}$	-OH	-CHO	$\begin{array}{c} O \\ \\ -\text{C}- \end{array}$	$\begin{array}{c} O \\ \\ -\text{C}-\text{O}- \end{array}$	H ₂ S
CH ₃ -	0.995	1.00	1.00	0.44	0.65	0.58	0.73	0.88
-CH ₂ -	0.995	1.00	1.00	0.44	0.65	0.58	0.73	
c/b _H = 12.0								

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5.5.5

Emissivity data for gases

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■ Tables 1a and 1b present the total emissivity of water vapor and carbon dioxide gas as a function of $P_a L$ and T_g , respectively. The quantity P_a is the partial pressure of the absorbing gas, H_2O or CO_2 ; L is the beam length of concern; and T_g is the gas temperature. The tables are presented for an equivalent broadening pressure ratio P_e equal to 1. The ratio is defined in the footnote to Table 1a and accounts for the fact that collisions between absorbing molecules and foreign gas

molecules are less effective in broadening the absorption lines than absorber-absorber collisions.

The tables are computed based upon the information contained in Table 1 of Section 2.9.5 in the manner illustrated there in the sample calculations. Also given in Section 2.9.5 are Hottel's and Penner's Rules (for low P_e and high P_e , respectively) whereby total absorptivity can be estimated from total emissivity.

Table 1a Total emissivity of H_2O at $P_e = 1^a$

Partial-pressure path-length product $P_a L$, atm m	Total emissivity, ϵ_g				
	$T_g = 400\text{ K}$	800 K	1200K	1600 K	2000K
0.001	0.0196	0.0060	0.0030	0.0017	0.0010
0.002	0.0318	0.0108	0.0057	0.0032	0.0020
0.004	0.0488	0.0187	0.0106	0.0062	0.0038
0.01	0.0786	0.0368	0.0273	0.0144	0.0091
0.02	0.1057	0.0638	0.0458	0.0291	0.0172
0.04	0.1435	0.0925	0.0726	0.0533	0.0319
0.10	0.2037	0.1481	0.1242	0.1035	0.0781
0.20	0.2574	0.2042	0.1800	0.1588	0.1303
0.40	0.3062	0.2708	0.2460	0.2213	0.1881
1.00	0.3757	0.3585	0.3389	0.3106	0.2740

^aNotes to Tables 1a, 1b, 2a, 2b: T_g is gas temperature in K. L is beam length in meters. P_a is the partial pressure of the absorbing species (H_2O or CO_2) in atm. P_e is effective broadening pressure defined by

$$P_e = \left\{ \frac{P}{P_o} [1 + (b-1)x_a] \right\}^n$$

where P is total pressure, P_o is one atmosphere, and x_a is the mole fraction of the absorbing species. $b = 8.6(T_o/T)^{1/2} + 0.5$, $n = 1$ for H_2O , $b = 1.3$, $n = 0.8$ for CO_2 . $T_o = 100\text{ K}$.

Table 1b Total emissivity of CO₂ at $P_e = 1^a$

Partial-pressure path-length product $P_a L$, atm m	Total emissivity, ϵ_g				
	$T_g = 400$ K	800 K	1200K	1600 K	2000K
0.001	0.0131	0.0195	0.0133	0.0068	0.0036
0.002	0.0182	0.0289	0.0211	0.0130	0.0072
0.004	0.0268	0.0376	0.0305	0.0204	0.0127
0.01	0.0437	0.0560	0.0460	0.0306	0.0202
0.02	0.0552	0.0725	0.0593	0.0415	0.0282
0.04	0.0737	0.0880	0.0769	0.0556	0.0394
0.10	0.0940	0.1131	0.1063	0.0815	0.0605
0.20	0.1114	0.1348	0.1269	0.1017	0.0775
0.40	0.1251	0.1566	0.1511	0.1228	0.0957
1.00	0.1529	0.1901	0.1894	0.1562	0.1230

^aSee footnote to Table 1a.

The emissivity grows with $P_a L$ because at constant T_g the number of absorbing molecules increases as $P_a L$ increases. At low values of $P_a L$ the absorption is weak, and each additional molecule adds equally to the absorption; hence ϵ_g is linear in $P_a L$. At higher values, the addition of greater opacity at the spectral centers of the lines has little additional effect there, and ϵ_g integrated over the lines grows as $\sqrt{P_a L}$. At still higher values of $P_a L$, the addition of greater opacity at the centers of the bands has little additional effect there, and ϵ_g grows primarily in the tails of the bands, in total even more slowly. Thus logarithmic rather than linear interpolation in $P_a L$ is indicated, to wit:

$$\epsilon_g(P_a L) = \epsilon_g(P_a L_2) \cdot \left(\frac{P_a L}{P_a L_2} \right)^n$$

$$n = \frac{\log[\epsilon_g(P_a L_2)/\epsilon_g(P_a L_1)]}{\log(P_a L_2/P_a L_1)}$$

where subscripts 1 and 2 refer to table values.

Table 2a Effect of broadening pressure on total emissivity of H₂ O^a

T_g , K	$P_a L$, atm m	ϵ_g			
		$P_e = 0.1$	0.3	3	10
400	0.001	0.0063	0.0112	0.0357	0.0468
	0.01	0.0264	0.0462	0.1206	0.1605
	0.10	0.0813	0.1320	0.2753	0.3362
	1.00	0.2058	0.2898	0.4637	0.5273
1200	0.001	0.0021	0.0026	0.0035	0.0069
	0.01	0.0113	0.0174	0.0263	0.0392
	0.10	0.0442	0.0721	0.1837	0.2086
	1.00	0.1397	0.2316	0.4171	0.4438
2000	0.001	0.0009	0.0009	0.0011	0.0019
	0.01	0.0065	0.0079	0.0106	0.0130
	0.10	0.0356	0.0551	0.0837	0.0937
	1.00	0.1246	0.1984	0.2999	0.3016

^aSee footnote to Table 1a.

The emissivity varies with T_g at fixed $P_a L$ primarily due to the change in the Planck spectral distribution with respect to the fixed spectral locations of the absorption bands, but secondarily because the bands become wider and some become stronger, but the number of molecules becomes fewer at elevated temperatures.

Tables 2a and 2b show the effect of broadening pressure ratio upon the total emissivity of the two gases. When the lines are weak and grow in strength linearly with $P_a L$, there is no collision broadening effect. When they are strong and grow as $\sqrt{P_a L}$, there is a $\sqrt{P_e}$ effect. At high temperatures, the band shape assumes more importance than the line shape, and the effect of P_e is slight. Again logarithmic interpolation is recommended.

Table 3a shows the total emissivity of hydrocarbon-air combustion gas mixtures for a total pressure of $P = 1$ atm. Tables 3b and 3c give the values for $P = 0.3$ and 3.0 atm. As stated in the footnote, the

Table 2b Effect of broadening pressure on total emissivity of CO₂ ^a

T_g , K	$P_a L$, atm m	ϵ_g			
		$P_e = 0.1$	0.3	3	10
400	0.001	0.0087	0.0093	0.0175	0.0218
	0.01	0.0198	0.0281	0.0546	0.0704
	0.10	0.0645	0.0763	0.1097	0.1194
	1.00	0.1175	0.1336	0.1652	0.1734
1200	0.001	0.0109	0.0131	0.0137	0.0137
	0.01	0.0402	0.0421	0.0461	0.0461
	0.10	0.0949	0.1044	0.1070	0.1070
	1.00	0.1704	0.1841	0.1891	0.1891
2000	0.001	0.0035	0.0035	0.0036	0.0036
	0.01	0.0199	0.0201	0.0202	0.0202
	0.10	0.0600	0.0603	0.0605	0.0605
	1.00	0.1225	0.1230	0.1230	0.1230

^aSee footnote to Table 1a.

Table 3a Total emissivity of H₂O–CO₂–N₂ mixtures, $p = 1 \text{ atm}^a$

$L, \text{ m}$	$x_{\text{H}_2\text{O}}$	x_{CO_2}	ϵ_g				
			$T_g = 400 \text{ K}$	800 K	1200 K	1600 K	2000 K
0.1	0.08	0.16	0.123	0.102	0.076	0.045	0.028
	0.13	0.13	0.137	0.112	0.084	0.051	0.028
	0.19	0.10	0.149	0.117	0.089	0.057	0.030
0.3	0.08	0.16	0.190	0.160	0.131	0.093	0.058
	0.13	0.13	0.215	0.175	0.143	0.105	0.069
	0.19	0.10	0.234	0.189	0.151	0.114	0.079
1.0	0.08	0.16	0.294	0.244	0.211	0.170	0.131
	0.13	0.13	0.315	0.267	0.235	0.193	0.153
	0.19	0.10	0.344	0.291	0.256	0.214	0.171
3.0	0.08	0.16	0.397	0.350	0.314	0.266	0.213
	0.13	0.13	0.430	0.380	0.345	0.296	0.242
	0.19	0.10	0.434	0.403	0.373	0.322	0.266

^aNotes to Tables 3a, 3b, 3c: T_g is gas temperature in K. L is beam length in meters. P is total pressure in atm. $x_{\text{H}_2\text{O}}$, x_{CO_2} are mole fractions. The fractions 0.08/0.16, 0.13/0.13, 0.19/0.10 correspond to stoichiometric combustion in air of C_xH_x (coal), C_xH_{2x} (oil), and C_xH_{4x} (gas), respectively.

compositions correspond to coal, oil, and gas fuels burned with stoichiometric air. Again logarithmic interpolation in L and P is recommended.

The data base for Table 1 in Section 2.9.5 does not go beyond 1400 K for CO₂ and 1100 K for H₂O. However, the band absorption correlations are based

upon the fairly accurate harmonic oscillator functions, and the Planck spectrum is very well known; thus extrapolation is felt to be warranted to the temperature values shown. The uncertainty in the tabulated values is $\pm 10\%$ within the data base and perhaps twice that uncertainty at the elevated temperatures.

Table 3b Total emissivity of H₂O–CO₂–N₂ mixtures, $p = 0.3 \text{ atm}^a$

$L, \text{ m}$	$x_{\text{H}_2\text{O}}$	x_{CO_2}	ϵ_g				
			$T_g = 400 \text{ K}$	800 K	1200 K	1600 K	2000 K
0.03	0.08	0.16	0.020	0.025	0.018	0.010	0.005
	0.13	0.13	0.022	0.025	0.018	0.009	0.004
	0.19	0.10	0.023	0.022	0.016	0.007	0.004
0.1	0.08	0.16	0.038	0.047	0.035	0.024	0.015
	0.13	0.13	0.044	0.048	0.037	0.024	0.014
	0.19	0.10	0.050	0.046	0.036	0.024	0.012
0.3	0.08	0.16	0.073	0.076	0.063	0.044	0.029
	0.13	0.13	0.082	0.077	0.063	0.048	0.031
	0.19	0.10	0.088	0.081	0.064	0.049	0.033
1.0	0.08	0.16	0.134	0.125	0.111	0.084	0.061
	0.13	0.13	0.144	0.127	0.115	0.088	0.066
	0.19	0.10	0.153	0.133	0.117	0.091	0.069

^aSee footnote to Table 3a.

Table 3c Total emissivity of $\text{H}_2\text{O}-\text{CO}_2-\text{N}_2$ mixtures, $P = 3.0 \text{ atm}^a$

$L, \text{ m}$	$x_{\text{H}_2\text{O}}$	x_{CO_2}	ϵ_g				
			$T_g = 400 \text{ K}$	800 K	1200K	1600 K	2000K
0.03	0.08	0.16	0.167	0.118	0.072	0.045	0.030
	0.13	0.13	0.187	0.132	0.080	0.052	0.030
	0.19	0.10	0.201	0.147	0.091	0.058	0.033
0.1	0.08	0.16	0.261	0.200	0.146	0.095	0.063
	0.13	0.13	0.290	0.226	0.169	0.110	0.070
	0.19	0.10	0.310	0.247	0.190	0.127	0.080
0.3	0.08	0.16	0.363	0.299	0.247	0.183	0.120
	0.13	0.13	0.400	0.331	0.280	0.216	0.153
	0.19	0.10	0.418	0.355	0.308	0.242	0.177
1.0	0.08	0.16	0.465	0.425	0.376	0.300	0.226
	0.13	0.13	0.488	0.456	0.415	0.336	0.262
	0.19	0.10	0.498	0.488	0.444	0.365	0.290

^aSee footnote to Table 3a.

5.5.6

Thermal conductivity of solids

P. E. Liley

■ In the tables that follow an attempt is made to give, as comprehensively as possible, a tabulation of the temperature dependence of thermal conductivity of elements, alloys, and other solids. In addition, a further tabulation is given of typical room temperature values of this property for other solids. In using the tables the following remarks should be kept in mind:

1. In structured materials such as crystals, wood, mica, etc., the property may be an acute function of direction of heat transfer.

2. Impurities, thermal history of the specimen, environmental effects (such as applied magnetic field) can sometimes markedly affect the property.

3. For low density insulation, thermal radiation should also be considered.

4. Exposure of the material to the actual environment can markedly affect the property due to such factors as contact resistance, degradation, oxidation, moisture seepage, etc.

5. At low temperatures, the thermal conductivity can vary rapidly (see Fig. 1) and also be a sensitive function of specimen purity. The tabulated values for the pure elements are for materials of highest purity that are generally available. The actual property for real substances may be much less.

6. Where there may be more than one state of the material, the tabulation given is for the polycrystalline state. Limitations of space have prevented a more detailed tabulation. Readers interested in exploring the subject further may find the publications given in [I-6] helpful.

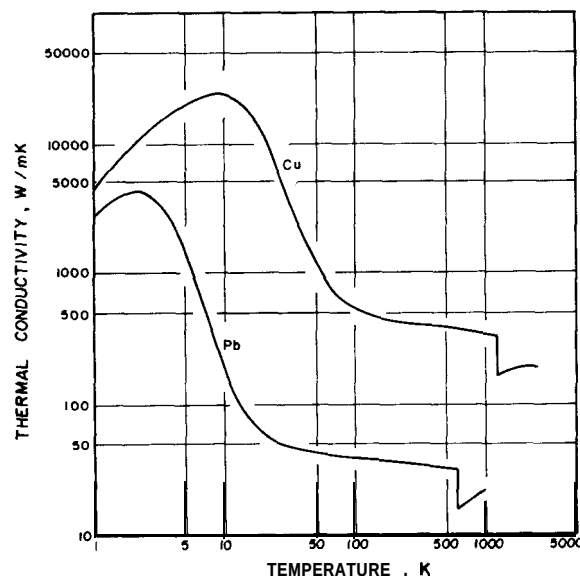


Figure 1 Relationship between thermal conductivity and temperature for copper and lead.

Table 1 Thermal conductivity of solids as a function of temperature, W/m K

Material	Conductivity at different temperatures, K																	
	10	20	40	60	80	100	150	200	250	300	400	500	600	800	1000	1200	1400	1500
Alumina	3 000	12 500	13 500	3 100	1 100	520	155	80	60	42	27	20	16	10	7.6	6.3	5.7	5.4
Aluminum	38 000	13 000	2 400	850	430	300	250	237	235	237	240	236	231	218	—	—	—	—
Antimony	480	230	110	75	58	46	36	30	26.7	24.3	21.3	19.5	18.3	16.8	—	—	—	—
Argon	5.6	1.5	0.7	0.3	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Arsenic	—	—	—	—	—	—	—	69	58	50	41	35	—	—	—	—	—	—
Barium	—	—	—	—	—	—	20.5	19.4	18.6	18.2	—	—	—	—	—	—	—	—
BaTiO ₃	10	18	21	19	16	13	8	5.9	4.8	4.1	3.5	3.0	—	—	—	—	—	—
Beryllium	1 800	3 480	4 620	2 980	1 620	890	450	300	235	200	160	139	126	106	91	79	69	64
Beryllia	—	—	—	—	—	—	—	—	—	—	198	153	114	60	33	22	17	17
Bismuth	225	100	46	30	24	19	12	9.7	8.6	7.9	7.0	6.6	—	—	—	—	—	—
Boron	175	250	430	360	260	190	94	55	—	—	—	—	—	—	—	—	—	—
Brass	5	12	24	33	40	46	62	74	92	114	134	143	146	150	—	—	—	—
Cadmium	1 200	270	140	115	106	103	101	99	98	97	95	92	—	—	—	—	—	—
Calcium	—	—	—	—	—	—	220	210	201	189	182	178	153	116	—	—	—	—
CaF ₂	2 800	2 500	800	125	60	40	23	18	15	12	—	—	—	—	—	—	—	—
CaO	—	—	—	—	—	—	—	—	—	—	129	99	85	79	74	72	70	69
Carbon	0.07	0.16	0.31	0.44	0.56	0.67	0.94	1.18	1.40	1.60	1.87	2.06	2.19	2.37	2.5	2.8	3.2	3.5
Cerium	1.1	1.9	3.2	4.3	5.2	6.0	7.7	9.0	10.3	11.4	13.3	15.0	16.5	19.3	21.8	—	—	—
Cesium	69	55	47	43	41	40	38	37	36	36	—	—	—	—	—	—	—	—
Chromium	385	595	425	250	185	160	130	110	100	94	91	86	81	71	65	62	59	57
Cobalt	265	440	375	250	195	165	140	120	110	100	85	75	67	58	52	49	42	42
Constantan	—	—	—	—	—	19	20	21	22	23	27	—	—	—	—	—	—	—
Copper	24 500	10 800	2 170	830	560	480	429	413	406	401	393	386	379	366	352	339	—	—
Duralumin	16	30	56	74	88	101	123	138	151	174	187	188	—	—	—	—	—	—
Dysprosium	10	14	14	13	12	10	9	10	10	11	11	12	12	14	15	17	18	19
Erbium	7.1	7.8	9.3	9.8	11	12	14	15	15	14	14	14	14	15	16	17	19	19
Eureka	—	—	—	—	—	—	—	20	21	22	24	25	—	—	—	—	—	—
Gadolinium	31	32	23	18	15	15	13	12	11	10	—	—	—	—	—	—	—	—
German silver	4.8	7.5	11.5	13.8	15.3	17	19	21	23	24	25	27	—	—	—	—	—	—
Germanium	1 770	1490	800	490	325	230	130	97	75	60	43	34	27	20	17	17	—	—
Gold	3 250	1 580	515	374	332	327	325	323	321	317	311	304	298	284	270	255	—	—
Hafnium	10	18	24	26	26	26	25	24	24	23	23	22	21	21	21	21	21	21
Hohnium	12	14	16	16	15	14	14	15	16	16	17	18	—	—	—	—	—	—
Indium	590	190	170	100	99	98	93	90	86	82	75	—	—	—	—	—	—	—
Iridium	1270	1 900	750	330	210	172	159	153	150	147	144	141	138	132	126	120	114	111
Iron	1480	1 540	625	285	175	134	104	94	87	80	70	61	55	43	32	28	31	32
Lanthanum	18	17	10	9	9	10	11	12	13	14	15	16	18	21	23	—	—	—
Lead	180	60	45	43	41	39.7	37.9	36.7	36.0	35.3	34.0	32.8	31.4	—	—	—	—	—
Lithium	610	720	345	175	120	105	95	90	87	85	80	—	—	—	—	—	—	—
LiF	11000	13 500	1300	280	146	95	42	27	—	—	—	—	—	—	—	—	—	—
Limestone	—	—	—	—	—	3.2	2.7	2.3	2.0	1.8	1.6	1.5	—	—	—	—	—	—
Lutetium	36	41	32	30	29	28	26	25	24	23	22	22	—	—	—	—	—	—
Magnesium	5 600	2 700	720	325	200	169	161	159	157	156	153	151	149	146	—	—	—	—
Manganese	1.6	2.4	3.6	4.5	5.3	5.8	6.6	7.2	7.5	7.8	7.9	8.0	—	—	—	—	—	—
Manganin	—	—	—	—	—	—	—	14	18	21	23	27	—	—	—	—	—	—
Mercury	46	40	36	34	33	32	30	29	—	—	—	—	—	—	—	—	—	—
Magnesium oxide	—	—	—	—	—	—	—	—	—	—	32.4	25.5	19.9	12.8	9.2	7.2	6.2	5.9
Molybdenum	150	285	355	260	210	180	149	143	140	138	134	130	126	118	112	105	100	98

	Monel	3.5	7.1	11.0	13.3	14.9	16	18	20	22	23	25	27						
Naphthalene						1.20	0.96	0.62	0.50	0.42	0.35	0.29	0.27						
Nickel	1810	1 650	580	310	210		165	120	105	98	91	80	72	66	68	72	76	80	83
Nimonic 75											13	15	17	18	21	25			
Niionic 80												12	14	15	18	23			
Niionic 90											12	13	15	16	19	23			
Nimonic 95												13	15	16	18	22			
Nimonic 100												12	13	14	16	20			
Niobium	295	250	95	66	58		55	53	53	53	54	55	57	58	61	64	68	71	72
Nylon	0.033	0.099	0.170	0.206	0.230	0.242													
Osmium	1020	1 600	640	220	140	115	96	91	89	88	87	87	87						
Palladium	1 150	600	175	98	81	77	73	72	72	72	74	76	80	87	94	102	107	110	
Phosphorus	7	27	44	40	35	31	23	18	14	12									
Platinum	1 230	500	140	95	82	78	74.0	72.6	71.8	71.6	71.8	72.3	73.2	75.6	79	83	87	90	
Plutonium					3.1	3.3	4.0	4.8	5.7	6.7	9.6								
Porcelain													1.45	1.7	2.0	2.2	2.4		
Potassium	460	165	115	110	108	107	105	104	104	102									
KCl	440	400	105	52	32	25	13	11	8	7	6	5							
Praseodymium					7	8	9	10	12	13	14	15	16	18	22				
Pyrex				0.34	0.46	0.57	0.76	0.89	0.95										
Quartz	8 000	3 600	850	410	240	200													
Rhenium	3 550	1 150	155	77	63	59	54	51	49	48	46	45	44	44	45	46	47	48	
Rhodium	2 780	3 650	1 020	380	240	190	158	154	152	150	146	141	136	127	121	116	112	110	
Rubber						0.14	0.15	0.15	0.16	0.16									
Rubidium	150	69	64	62	61	60	59	59	59	58									
Ruby	650	1 335	1700	1 000	500	290													
Ruthenium	1500	2 260	950	310	185	155	128	118	117	117	114	111	108	102	98	94	91	90	
Salt	770	330	82	44	30	24	15	11	8.9	7.1	4.4	3.4							
Sapphire	2 600	14 600	16 500	4 400	1 175	480	150	82	58	46	32	24							
Scandium	7	12	14	14	14	14	15	15	16	16	16	17							
Silicon	2 330	4 980	3 530	2 110	1 340	884	410	260	190	150	99	76	62	42	31	26	24	23	
Silumin												177	181						
Silver	16 800	5 100	1050	550	470	450	432	420	429	429	425	419	412	396	379	361			
Silver solder	1650	720	179	85	54	39	23	16	13	10	7.6	6.0							
Sodium	2 200	610	190	145	135	136	140	142	143	141									
NaF	4 500	3 100	560	240	120	85	55	45	38	36									
Sulfur	8.2	2.4	1.1	0.8	0.72	0.56	0.43	0.36	0.31	0.27									
Tantalum	107	142	87	65	60	59	58	58	57	58	58	59	59	59	60	61	62	62	
Technetium											51	50	50	50	52	55			
Teflon	0.094	0.142	0.194	0.220	0.23	0.23	0.24	0.25	0.25	0.26									
Terbium	19	23	19	17	15	14	12	10	10	11									
Thallium	190	80	65	61	58	56	52	49	48	46	44	42							
Thoria									16	13	10	8	6	5	4	3	3	2	
Thorium	470	170	85	69	63	60	56	55	54	54	55	55	56	57	58	59	60	61	
Thulium	23	18	11	11	13	14	15	16	17	17									
Tin	1900	320	135	104	92	85	78	73	70	67	62	60							
Titanium	14	28	39	36	33	31	27	25	23	21	20	20	19	19	21	22	24	25	
Titanium oxide	1 000	850	130	60	31	20	11	9	8.5	8	6	5	4	3	3	3	3	3	
Tungsten	9 700	4 050	690	310	230	208	192	185	180	174	159	146	137	125	118	112	108	106	
Uranium	10	16	18	20	21	22	24	25	26	28	30	33	34	39	44	49	56		
Vanadium	14	26	39	41	39	36	32	31	31	31	31	32	33	36	38	41	43	45	
Yttrium	7	13	15	16	16	16	16	17	17	17	18	19	21	23	25				
Zinc	4 750	1 000	280	160	130	117	117	118	118	116	111	107	103						
Zirconium	99	108	59	44	37	33	28	25	24	23	22	21	21	21	23	26	28	29	
Zirconium oxide												2.1	2.1	2.2	2.2	2.3	2.3	2.4	

Table 2 Thermal conductivity of materials at room temperature, W/m K

Material			Value	Material			Value
Stainless steel	201		16.3	Hastelloy	B		10.4
	202		16.3		C		8.8
	301		16.2		D		20.9
	302		16.2		G		10.8
	304		16.3		X		9.0
	304L		16.3	Incoloy	800		12.2
	309		13.8		901		13.4
	310		13.8	Nimonic	80A		12.2
	316		16.3		600		15.0
	318L		16.3	Inconel	610		15.0
	321		15.8		625		10.8
	330		13.0		700		12.4
	347		15.8		705		15.0
	410		24.9		722		14.7
	414		24.9		X750		14.7
	420		24.9	Monel	400		25.1
	430		25.9		401		19.2
	431		20.2		R405		25.9
	446		20.9		404		25.0
cast stainless	CA15		24.5	Aluminum alloy	411		26.8
	CA40		24.5		505		19.6
	CB30		22.1		506		20.9
	CC50		21.8		1100		340
	CF8		15.9		3003		192
	CF8M		16.2		5052		137
	CF20		15.9		5086		135
	CK20		14.2		6063		186
	CN7M		20.9		7075		120
	HU		15.4				
	Hw		13.3				
	HA		29.4				
	HC		30.9				
	HD		30.9				

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5.5.7

Emissivity of solids

P. E. Liley

■ Two tables of the emissivity of metals and other materials are presented. One is a temperature-dependence table covering the range 100 to 1 **500 K**. The other is a room temperature tabulation. Both tables only tabulate the total normal (nt), hemispherical total (ht) or undefined total emissivity. No attempt has been made to list other dependence, such as on wavelength, or other properties, such as absorptivity or reflectivity. The selection of materials also requires comment. While the selected references **listed** below tabulate properties for many

more materials and surface conditions the surfaces have been found to be very sensitive to thermal history, method of preparation, and the effect of the environment. Topographical, chemical, and structural characteristics all influence the surface and hence the **emissivity**. Large variations in the properties occur with little or no apparent change in the preparation of the specimen. The tables presented here should therefore be regarded as giving an approximate guide to the actual behavior which one may encounter.

Table 1 Emissivities of metals and compounds as a function of temperature

Material	Type	Emissivity at different temperatures, K									Remark(s)
		100	200	400	600	800	1000	1200	1400	1500	
Aluminum	ht	0.02	0.03	0.05	0.06	0.07					Polished foil
Al₂O₃	nt			0.78	0.69	0.61	0.54	0.49	0.42	0.40	
Al alloy 245T	ht	0.02	0.03	0.04	0.05	0.06	0.08				Polished
BN	nt					0.75	0.75	0.74	0.74	0.74	
CdS	nt	0.62	0.56	0.27	0.16						
Carbon	nt			0.85	0.84	0.83	0.83	0.82	0.82	0.82	
Copper	ht	0.02	0.02	0.03	0.03	0.04	0.04	0.05	0.05	0.06	Polished
Copper	ht				0.50	0.58	0.80				Oxidized at 1 000 K
GdO	nt					0.35	0.29	0.25	0.16	0.13	
Gold	ht	0.01	0.02	0.03	0.05	0.06	0.07	0.08			Polished foil
HfB₂	nt					0.41	0.46	0.52	0.72	0.76	
HfC	nt						0.98	0.98	0.98	0.98	
HfO₂	nt						0.80	0.81	0.82	0.83	
Iron	ht	0.02	0.05	0.09	0.14	0.20	0.25	0.30	0.35	0.42	Polished
Iron oxides	nt						0.84	0.84	0.82		
MgO	nt	0.72	0.72	0.73	0.62	0.52	0.47	0.41	0.36	0.31	
Molybdenum	ht	0.03	0.05	0.07	0.08	0.10	0.12	0.14	0.17	0.18	Polished
Monel	ht	0.14	0.14	0.15	0.17	0.19	0.22	0.26	0.34		Polished
NaCl	ht	0.64	0.44	0.24							
Niobium	ht	0.03	0.04	0.06	0.08	0.10	0.13	0.15	0.17	0.18	Polished

Table 1 Emissivities of metals and compounds as a function of temperature (Continued)

Material	Type	Emissivity at different temperatures, K									Remark(s)
		100	200	400	600	800	1000	1200	1400	1500	
NbC	ht								0.43	0.44	
NbC	nt					0.33	0.64	0.74	0.84	0.84	
Nickel	ht	0.07	0.08	0.10	0.11	0.12	0.15	0.17	0.21	0.23	Polished
Platinum	ht	0.03	0.05	0.07	0.09	0.11	0.13	0.15	0.17	0.18	Polished
Rhenium	ht	0.10	0.12	0.13	0.15	0.16	0.18	0.19	0.20	0.21	Polished
Silver	ht	0.01	0.02	0.02	0.03	0.03	0.03	0.04	0.04	0.05	Polished
Sapphire	ht		0.48	0.58							
SE	nt			0.86	0.86	0.85	0.85	0.85	0.85	0.84	
Si₃N₄	nt			0.93	0.90	0.86	0.84	0.81	0.72	0.70	
SiO₂ (fused)	ht	0.73	0.72	0.79							
Tantalum	ht		0.01	0.03	0.05	0.08	0.11	0.13	0.16	0.18	Polished
TaC	ht				0.29	0.32	0.35	0.38	0.41	0.42	
TaC	nt					0.38	0.52	0.65	0.73	0.75	
TaN	nt					0.70	0.75	0.78	0.81	0.83	
ThO	nt						0.29	0.29	0.28		
TiC	ht					0.49	0.54	0.60	0.62	0.64	
TiC	nt					0.54	0.68	0.75	0.86	0.87	
TiN	nt					0.43	0.54	0.63	0.75	0.71	
TiO₂	nt					0.50	0.47	0.42	0.39	0.38	
Ti alloy A 11 O-AT	ht	0.12	0.14	0.17	0.21	0.23	0.26	0.28	0.29	0.30	Polished
Tungsten	ht			0.03	0.05	0.07	0.09	0.12	0.16	0.17	Polished
Uranium	ht				0.30	0.32	0.36	0.38			Polished
ZrB₂	nt					0.35	0.47	0.56	0.69	0.72	
ZrC	ht						0.54	0.50	0.46	0.42	
ZrO₂	nt	0.88	0.86	0.74	0.63	0.51	0.44	0.42	0.40	0.41	
ZnS	ht	0.54	0.56	0.30							
ZnSe	ht	0.54	0.43	0.22							

Table 2 Emissivity of miscellaneous materials at room temperature

Material	Type	Value	Material	Type	Value
Al alloy 245T	n	0.09	Chromium	n	0.08
Al hydroxide powder	n	0.28	Clay, fired	nt	0.91
Al rooting	n	0.22	Co alloy N155	n	0.09
Alumina	nt	0.06-0.75	Coal, ground	nt	0.80
Asbestos, board	nt	0.96	Coatings		0.03-0.85
Asbestos, cloth	nt	0.90	Concrete, rough	nt	0.94
Asbestos, paper	nt	0.94	Corundum, rough	nt	0.86
Asbestos, slate	nt	0.97	Cu plate, oxidized	n	0.78
BaCl₂ , powder	n	0.65	Cupric oxide	n	0.10
Beechwood	nt	0.94	Dow metal	n	0.15
Bismuth	n	0.05	Earthenware, glazed		0.90
Brass, oxidized	ht	0.60	Earthenware, matte		0.93
Brass, polished	ht	0.04	Ebonite	n	0.89
Brick, rough	nt	0.93	Enamels	n	0.90
Brick, smoothed	nt	0.93	Everdur alloy	n	0.11
CaCO₃ powder	n	0.30	Frost, rime		0.99
Carbon	n	0.80	Glass, polished	nt	0.90-0.95
Ceria	ht	0.40-0.70	Glass, smooth	nt	0.94

Table 2 Emissivity of miscellaneous materials at room temperature (Continued)

Material	Type	Value	Material	Type	Value
Granite	nt	0.44	Paints, flat black		0.88
Graphite powder	n	0.07	Paints, gloss black		0.90
Gravel	nt	0.28	Paints, gray		0.95
Gypsum	nt	0.80-0.90	Paints, green		0.95
Ice, crystal	nt	0.99	Paints, oil		0.90-0.96
Ice, smooth	nt	0.97	Paper, roofing	nt	0.91
Inconel B	n	0.20	Paper, white	nt	0.80-0.95
Inconel X	n	0.21	Plaster of Paris	nt	0.92
Iron, ARMCO	n	0.10	Plaster, rough	nt	0.92
Iron, ARMCO, oxidized	n	0.30	Porcelain, glazed	nt	0.92
Iron, cast, oxidized		0.57	Quartz	nt	0.89
Iron, cast, polished		0.21	Quartz, flour	nt	0.90
Iron, electrolytic, oxidized		0.79	Quartz, rough	nt	0.89
Iron, electrolytic, polished		0.05	Refractory, black		0.94
Iron, rusted	n	0.85	Refractory, light		0.92
Iron, wrought, dull	n	0.94	Refractory, white		0.90
Iron, wrought, polished		0.29	Resins		0.79-0.83
Kaolin, powder	n	0.30	Rubber, hard	nt	0.92
Kieselguhr	n	0.25	Rubber, soft	nt	0.86
Lacquers		0.05-0.96	Sand	nt	0.76
Lampblack	nt	0.95	Sandstone, red	nt	0.59
Lead oxide powder	n	0.29	Sawdust	nt	0.75
Lead, red	nt	0.93	Shellac, dull	n	0.91
Leather	n	0.77	Shellac, polished	n	0.82
Lime, dolomitic	nt	0.40	Slag, boiler	n	0.95
Limestone	nt	0.95	Slate	nt	0.65-0.85
Lineoleum	nt	0.89	Slate, dark gray	nt	0.90
Magnesia	nt	0.71	Slate, silver gray	nt	0.80
Manganin, polished	n	0.05	Snow, fine		0.82
Marble, polished	nt	0.92	soil	nt	0.38
Marble, smooth	nt	0.56	soot, lamp	nt	0.95
Marble, white	nt	0.95	Spruce, sanded	nt	0.82
Monel KS 700	n	0.22	Stellite	n	0.18
Mortar, lime	nt	0.92	Stonework	nt	0.93
Mold	nt	0.64	Talc powder	n	0.24
Mica	nt	0.75	Ti alloy Al 10AT	n	0.59
Nickel , oxidized	n	0.26	Ti alloy AMS 4901	n	0.19
Oak, planed	nt	0.91	Tungsten	n	0.02
Paints, aluminum		0.27-0.80	Varnish, black, dull		0.91
Paints, bronze		0.50-0.55	Varnish, shiny		0.82
Paints, flat white		0.91	Wood, planed	nt	0.78

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5.5.8

Elastic properties of solids

S. F. Pugh

■ Comparison of the values for an elastic property of a particular metal or alloy quoted in the various data books and published in original papers indicates a remarkably wide spread. For any given material, values differing by 2% are quite common. Therefore any calculation using elastic properties as input data should explicitly declare the values that have been taken.

The sources of error in measurement of elastic properties arise partly from difficulties in measurement of elastic strain. The quantity to be measured is at most a few parts per thousand change in length and to be measured with two to three figure accuracy. Other sources of error are more fundamental. For example, in the preparation of specimens for measurement of elastic properties, a certain degree of preferred orientation of the individual grains is introduced, thus affecting the properties in the ways described in Sec. 5.45. It should also be realized that data for isotropic material may not best represent the properties of components that might have developed preferred orientation of the grains during fabrication. Finally, both at room temperature and to a greater extent at elevated temperatures and at high stress levels stress-strain response of a specimen is time dependent and structure sensitive.

Where high accuracy is required as for example, in attempting to understand the performance of a particular fabricated heat exchanger, the best procedure would be to measure the elastic properties on samples of the actual materials at the appropriate temperature and strain rate.

Tables 1 and 2 show single crystal elastic coeffi-

cients for hexagonal and cubic metals, respectively [1, 2]. They are included here to indicate the extent to which elastic anisotropy can be expected in wrought polycrystalline materials with preferred orientation of the grains.

The only values for Young's modulus tabulated here are derived from [3], which was produced specifically for tubular heat exchanger designers in the U.S.

Some of the reference books containing tabulated elastic constants data for structural materials are listed below with an indication of the types of data available, [4 to 10].

The data in Tables 1-3 are in the SI units, **pascals** (Pa), where $1 \text{ Pa} = 1 \text{ N/m}^2$; 1 pound per square inch = $6.894757 \times 10^3 \text{ Pa}$; and $1 \text{ dyne/cm}^2 = 0.1 \text{ Pa}$.

Table 1 Single crystal elastic constants of some hexagonal metals in gigapascals^a

Metal	Shear constants						
	C_{11}	C_{33}	C_{12}	C_{13}	C_{44}	C_{66}	$C^b/6$
Beryllium	299	342	28	11	166	136	161
Zinc	161	66	34	50	40	63	21
Magnesium	57	62	23	19	17	17	21
Zirconium	144	165	73	65	33	36	41
Titanium	163	180	93	62	47	35	62
Cadmium	115	51	40	40	20	38	16

^aFrom Tang et al. [1]. (Giga = 10^9 .)

^b $C = C_{11} + C_{12} + 2C_{33} - 4C_{13}$

Table 2 “c” Coefficients for some cubic metals in gigapascals^a

Metal	C_{11}	C_{12}	C_{44}	Anisotropy ratio
Silver	120	90	44	0.34
Aluminum	112	66	28	0.82
Copper	168	121	75	0.31
Brass, 28% Zn	147	111	72	0.25
α -Iron (ferrite)	237	141	116	0.41
Molybdenum	455	176	110	1.27
Nickel	251	157	121	0.39

^aFrom Smithells [2].**Table 3 Quasistatic Young's modulus values in gigapascals as a function of temperature^a**

Material	Value at different temperatures, K												
	300	325	350	425	475	525	575	650	700	750	800	850	925
Carbon steel	200	—	197	194	190	185	180	169	159	145	128	—	—
Aust. stainless steel	193	—	187	183	179	174	170	164	159	154	150	—	—
Carbon-MO and low chrome steels (through 3% chrome)	206	—	203	200	197	193	190	183	177	169	161	145	108
Intermediate Cr-MO steels (5-9% Cr)	189	—	187	185	182	180	176	172	167	162	158	153	143
Straight chrome steels (12, 17, 27% Cr)	201	—	197	195	191	187	180	171	159	145	131	113	84
Gray cast iron	92	—	91	89	87	84	81	76	70	—	—	—	—
Nickel-copper alloy 400	179	—	179	178	177	175	171	159	145	128	113	102	90
Cupro nickels (70-30, 80-20, 90-10)	130	—	127	124	121	119	116	112	105	—	—	—	—
Aluminum	73	—	73	72	70	66	59	—	—	—	—	—	—
Ni-Cr-Fe alloy 600	219	—	213	210	207	204	201	197	192	—	174	—	138
Ni-Fe-Cr alloy 800	196	—	191	188	185	181	178	174	170	—	—	—	—
Ni-Fe-Cr-Mo-Cu alloy 825	195	—	—	—	185	—	—	174	—	—	—	—	—
Ni-Mo alloy B	203	—	—	—	—	—	190	—	—	—	—	—	—
Ni-Mo-Cr alloy C-276	—	205	—	—	188	—	—	—	175	—	—	—	—
Nickel	207	—	204	201	197	193	189	185	181	177	173	169	163
Copper	110	109	108	106	104	101	98	94	—	—	—	—	—
Commercial brass	97	96	94	93	90	88	85	81	—	—	—	—	—
Leaded tin bronze	90	89	87	85	83	81	78	75	—	—	—	—	—
Phosphor bronze	103	102	99	96	93	89	82	72	60	—	—	—	—
Muntz	105	103	96	89	81	75	—	—	—	—	—	—	—
Admiralty	110	—	107	101	93	86	76	66	52	—	—	—	—
Titanium grade 2	—	117	100	—	90	—	79	—	—	—	—	—	—
Zirconium	—	99	—	92	—	80	—	68	—	—	—	—	—
Cr-Mo alloy KM-27	215	—	198	188	187	—	—	—	—	—	—	—	—
Cr-Ni-Fe-Mo-Cu-Cb alloy 20 Cb	193	—	—	—	—	—	—	—	—	—	—	—	—

From[3].

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5.5.9

Properties of liquid heavy water

G. Ulrych

■ Critical properties: $p_c = 216.59$ bar; $T_c = 370.66^\circ\text{C}$;
 $T_c = 643.81$ K; $\rho_c = 350$ kg/m³; molecular weight:
 $\bar{M} = 20.028$ kg/kmol; triple point: $T_t = 3.82^\circ\text{C}$.

Table 1 Properties of liquid heavy water at $p=1$ bar^{a, b}

T , °C	ρ , kg/m ³	c_p , kJ/kg K	β , 10 ⁻³ /K	λ , 10 ⁻³ W/m K	η , 10 ⁻⁶ kg/m s	ν , 10 ⁻⁶ m ² /s	κ , 10 ⁻⁶ m ² /s	Pr
3.82	1 105.5	4.210	-0.132	564	2 058	1.861	0.121	15.35
10.00	1 106.0	4.231	-0.027	570	1 689	1.527	0.122	12.53
20.00	1 105.4	4.242	0.121	580	1 253	1.133	0.124	9.17
30.00	1 103.3	4.240	0.242	589	972	0.881	0.126	7.00
40.00	1 100.0	4.232	0.343	597	785	0.713	0.128	5.56
50.00	1 095.7	4.220	0.428	605	648	0.591	0.131	4.52
60.00	1 090.6	4.207	0.502	611	545	0.5 00	0.133	3.75
70.00	1 084.7	4.194	0.569	617	468	0.432	0.136	3.18
80.00	1 078.2	4.181	0.631	621	409	0.379	0.138	2.75
90.00	1 071.0	4.170	0.689	625	363	0.339	0.140	2.42

^a T , temperature; ρ , density; c_p , specific heat capacity; β , thermal expansion coefficient; λ , thermal conductivity; η , dynamic viscosity; ν , kinematic viscosity; κ , thermal diffusivity; Pr, Prandtl number.

^bProperties according to [6,9].

Table 2 Density ρ of liquid heavy water as a function of pressure and temperature^a

Pressure, bar	Temperature, °C								
	3.82	20	50	100	150	200	250	300	350
1	1 105.5	1 105.4	1 095.7	1 063.4					
10	1 106.0	1 105.9	1 096.1	1 063.8	1 017.6				
50	1 108.3	1 108.0	1 098.1	1 065.9	1 020.1	961.2	885.1		
100	1 111.1	1 110.6	1 100.5	1 068.5	1 023.2	965.3	891.5	788.3	
150	1 113.9	1 113.1	1 102.9	1 071.0	1 026.3	969.4	897.5	800.3	
170	1 115.0	1 114.1	1 103.9	1 072.0	1 027.5	970.9	899.9	804.7	625.8

^a ρ in kg/m³.

Table 3 Constant pressure specific heat c_p of liquid heavy water as a function of pressure and temperature'

Pressure, bar	Temperature, °C								
	3.82	20	50	100	150	200	250	300	350
1	4.210	4.242	4.220	4.161					
10	4.207	4.239	4.218	4.159	4.172				
50	4.189	4.225	4.209	4.151	4.160	4.295	4.630		
100	4.167	4.208	4.197	4.140	4.145	4.269	4.571	5.424	
150	4.145	4.192	4.186	4.130	4.131	4.246	4.518	5.218	
170	4.136	4.186	4.182	4.126	4.126	4.237	4.499	5.151	9.933

 $^a c_p$ in kJ/kg K.**Table 4 Thermal expansion coefficient $\beta = (1/v)(\partial v/\partial T)_p$ of liquid heavy water as a function of pressure and temperature'**

Pressure, bar	Temperature, °C								
	3.82	20	50	100	150	200	250	300	350
1	-0.132 1	0.121 2	0.428 0	0.745 4					
10	-0.130 0	0.122 9	0.428 1	0.743 8	1.032 9				
50	-0.119 8	0.1305	0.428 5	0.737 0	1.018 1	1.375 8	1.977 5		
100	-0.105 5	0.140 1	0.429 1	0.728 9	1.000 6	1.340 3	1.886 4	3.288 5	
150	-0.089 8	0.149 6	0.429 6	0.721 1	0.984 0	1.307 4	1.807 0	2.956 2	
170	-0.083 2	0.153 4	0.429 9	0.718 1	0.977 6	1.294 9	1.778 0	2.848 5	11.0377

 $^a \beta$ in $10^{-3}/K$.**Table 5 Thermal conductivity λ of liquid heavy water as a function of pressure and temperature'**

Pressure, bar	Temperature, °C								
	3.82	20	50	100	150	200	250	300	350
1	564	580	605	628					
10	565	580	605	628	620				
50	567	583	608	630	624	591	536		
100	571	586	610	632	628	594	541	471	
150	574	589	613	635	632	597	546	478	
170	575	591	614	635	634	598	548	481	368

 $^a \lambda$ in 10^{-3} W/m K.**Table 6 Dynamic viscosity η of liquid heavy water as a function of pressure and temperature'**

Pressure, bar	Temperature, °C								
	3.82	20	50	100	150	200	250	300	350
1	2 057.9	1 252.9	647.8	325.4					
10	2 056.9	1 252.9	648.1	325.6	207.6				
50	2 052.5	1 252.5	649.1	326.6	209.3	150.1	116.7		
100	2 046.6	1 251.9	650.4	327.9	211.5	151.2	118.0	94.2	
150	2 040.4	1 251.2	651.7	329.3	213.7	152.3	119.3	95.7	
170	2 837.8	1 250.9	652.2	329.8	214.6	152.8	119.9	96.4	68.3

 $^a \eta$ in 10^{-6} kg/m s.

Table 7 Kinematic viscosity ν of liquid heavy water as a function of pressure and temperature'

Pressure, bar	Temperature, °C								
	3.82	20	50	100	150	200	250	300	350
1	1.861	1.133	0.591	0.306					
10	1.860	1.133	0.591	0.306	0.204				
50	1.852	1.130	0.591	0.306	0.205	0.156	0.132		
100	1.842	1.127	0.591	0.307	0.207	0.157	0.132	0.119	
150	1.832	1.124	0.591	0.307	0.208	0.157	0.133	0.120	
170	1.828	1.123	0.591	0.308	0.209	0.157	0.133	0.120	0.109

ν in $10^{-6} \text{ m}^2/\text{s}$.

Table 8 Prandtl number of liquid heavy water as a function of pressure and temperature

Pressure, bar	Temperature, °C								
	3.82	20	50	100	150	200	250	300	350
1	15.35	9.17	4.52	2.16					
10	15.32	9.15	4.52	2.15	1.40				
50	15.15	9.08	4.50	2.15	1.40	1.09	1.01		
100	14.94	8.99	4.47	2.15	1.40	1.09	1.00	1.08	
150	14.74	8.90	4.45	2.14	1.40	1.08	0.99	1.05	
170	14.66	8.87	4.44	2.14	1.40	1.08	0.98	1.03	1.85

Table 9 Thermal diffusivity κ of liquid heavy water as a function of pressure and temperature'

Pressure, bar	Temperature, °C								
	3.82	20	50	100	150	200	250	300	350
1	0.121	0.124	0.131	0.142					
10	0.121	0.124	0.131	0.142	0.146				
50	0.122	0.125	0.131	0.142	0.147	0.143	0.131		
100	0.123	0.125	0.132	0.143	0.148	0.144	0.133	0.110	
150	0.124	0.126	0.133	0.143	0.149	0.145	0.135	0.114	
170	0.125	0.127	0.133	0.144	0.149	0.145	0.135	0.116	0.059

κ in $10^{-6} \text{ m}^2/\text{s}$.

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5.5.10

Physical properties of liquids at temperatures below their boiling point

Clive F. Beaton

■ Section 5.5.1 gives data for saturated liquids and vapors at temperatures and corresponding pressures along the saturation curve. The tables in Section 5.5.1 have a lower limit corresponding to the normal boiling point of the fluids concerned (i.e., the saturation temperature at 101.3 kPa). Since the properties of liquids are relatively insensitive to pressure, the tables given in Section 5.5.1 can be used to estimate values of the liquid physical properties over the temperature range covered and for pressures above the saturation pressure. The tables in this section supplement the saturation property tables by giving values for liquid physical properties at temperatures below the boiling point.

The tables given in the present section are derived from the tables of physical properties given in the *Wärmeatlas* and supplemented from other data collections (Refs. 1-6). In preparing these tables, the following rules and procedures have been observed:

1. Following the precedent of Sections 5.5.1 and 5.5.2, all of the physical properties for a given substance have been grouped together. In *the Wärmeatlas* tables, the data were grouped under the specific property rather than under the substance.

2. An extensive search has been made to discover reported values for each property, but when no values were found an estimated value has been given based on well-tried prediction procedures such as those reported in the earlier sections of this Handbook (see Sections 5.1.3 and 5.1.4). These values are indicated in parentheses in the present tables.

3. The tables are nominally for atmospheric pressure. Conditions in which the fluid is in the vapor form

at this pressure are indicated by V in the tables. Conditions in which the substance is in the solid form are indicated by S.

4. For convenience, data for the chemical formula, molecular weight, melting point, boiling point, critical temperature, and critical pressure are included in the tables for each substance. The values for these properties given in the VDI tables are in close agreement with the values given in the saturation property tables (Section 5.5.1), but where there are slight differences, and to avoid confusion, the values from Section 5.5.1 are repeated here where appropriate.

Data are included in the present tables for the following substances:

NORMAL PARAFFINS

Methane
Ethane
Propane
Butane
Pentane
Hexane
Heptane
Octane
Nonane
Decane
Undecane
Dodecane
Tridecane
Tetradecane
Pentadecane
Hexadecane

Heptadecane	Vinylbenzene
Octadecane	Propylbenzene
Nonadecane	Isopropylbenzene
Eicosane	Butylbenzene
ISOPARAFFINS	Pentylbenzene
2-Methylpropane	Hexylbenzene
2-Methylbutane	o-Xylene
2-Methylpentane	m-Xylene
3-Methylpentane	p-Xylene
2,2-Dimethylpropane	1,2,3-Trimethylbenzene
2,2-Dimethylbutane	1,2,4-Trimethylbenzene
2,3-Dimethylbutane	1,3,5-Trimethylbenzene
OLEFINS	1,2,3,4-Tetramethylbenzene
Ethylene	1,2,3,5-Tetramethylbenzene
Propylene	1,2,4,5-Tetramethylbenzene
Butene- 1	Pentamethylbenzene
Pentene- 1	Hexamethylbenzene
Hexene- 1	Diphenyl
Heptene- 1	Diphenylmethane
Octene- 1	Triphenylmethane
Propadiene	Naphthalene
Butadiene- 1,2	1-Methylnaphthalene
Butadiene- 1,3	2-Methylnaphthalene
Pentadiene- 1,2	1-Ethylnaphthalene
Pentadiene- 1,trans 3	2-Ethylnaphthalene
Pentadiene- 1,4	ALCOHOLS
Pentadiene-2,3	Methanol
ACETYLENES	Ethanol
Acetylene	1-Propanol
Methyl acetylene	1-Butanol
Ethyl acetylene	1-Pentanol
Dimethyl acetylene	1-Hexanol
NAPHTHENES	1-Heptanol
Cyclopropane	1-Octanol
Cyclobutane	Isopropanol
Cyclopentane	Isobutanol
Methylcyclopentane	Isopentanol
Ethylcyclopentane	<i>t</i>-Butyl alcohol
Propylcyclopentane	Ethylene glycol
Butylcyclopentane	1,3-Propylene glycol
Pentylcyclohexane	Glycerol
Hexylcyclohexane	Cyclohexanol
Cyclohexane	Benzyl alcohol
Methylcyclohexane	PHENOLS
Ethylcyclohexane	Phenol
Isopropylcyclohexane	<i>o</i>-Cresol
Butylcyclohexane	m-Cresol
Pentylcyclohexane	p-Cresol
Hexycyclohexane	ESTERS
Cyclopentene	Methyl formate
Cyclohexene	Ethyl formate
AROMATICS	Propyl formate
Benzene	Methyl acetate
Toluene	Ethyl acetate
Ethylbenzene	Propyl acetate

Methyl propionate	Dichlorodifluoromethane (Refrigerant 12)
Ethyl propionate	Trichlorofluoromethane (Refrigerant 11)
Propyl propionate	1, 1, 1-Trifluoroethane
Methyl butanoate	Chloroethane
Ethyl butanoate	1,1-Dichloroethane
Methyl benzoate	1,2-Dichloroethane
Ethyl benzoate	1, 1, 1-Trichloroethane
Methyl salicylate	1,1,2,2-Tetrachloroethane
ALDEHYDES	Pentachloroethane
Formaldehyde	Bromoethane
Acetaldehyde	1,2-Dibromoethane
Paraldehyde	Tetrachlorodifluoroethane (Refrigerant 112)
Furfural	Trichlorotrifluoroethane (Refrigerant 113)
Benzaldehyde	Dichlorotetrafluoroethane (Refrigerant 114)
Salicylaldehyde	Chloropropane
KETONES	Chlorobutane
Ketene	Chloropentane
Acetone	Vinyl chloride
Methyl ethyl ketone	1,1-Dichloroethylene
Diethyl ketone	Trichloroethylene
Dipropyl ketone	Tetrachloroethylene
Acetophenone	Fluorobenzene
Benzophenone	Chlorobenzene
CARBOXYLIC ACIDS	Bromobenzene
Formic acid	Iodobenzene
Acetic acid	Benzyl chloride
Propionic acid	m-Chlorotoluene
Butyric acid	AMINES
Pentanoic acid	Methylamine
Hexanoic acid	Dimethylamine
Acetic anhydride	Trimethylamine
Propionic anhydride	Ethylamine
ETHERS	Dietylamine
Dimethyl ether	Triethylamine
Diethyl ether	Isopropylamine
Methyl propyl ether	Piperidine
Ethyl propyl ether	Pyridine
Methyl <i>n</i> -butyl ether	Aniline
Dipropyl ether	Methylaniline
Ethylene oxide	Dimethylaniline
Propylene oxide	Diethylaniline
Furan	NITRILES
1,4-Dioxan	Acetonitrile
HALOGENATED HYDROCARBONS	Propionitrile
Chloromethane	Butyronitrile
Dichloromethane	AMIDES
Trichloromethane	Formamide
Carbon tetrachloride	NITRO DERIVATIVES
Bromomethane	Nitromethane
Dibromomethane	Nitrobenzene
Tribromomethane	o-Nitrotoluene
Tetrabromomethane	m-Nitrotoluene
Chlorodifluoromethane (Refrigerant 22)	p-Nitrotoluene
Chlorotrifluoromethane (Refrigerant 13)	ORGANIC SULFUR COMPOUNDS
Dichlorofluoromethane (Refrigerant 2 1)	Methyl mercaptan

Ethyl mercaptan Dimethyl sulfide Diethyl sulfide Thiophene INORGANIC SUBSTANCES Hydrogen fluoride Hydrogen chloride Hydrogen bromide Hydrogen iodide Hydrogen cyanide Hydrogen sulfide Air Ammonia Nitrogen dioxide Carbon monoxide Carbon dioxide Carbonyl sulfide	Carbon disulfide Sulfur dioxide Phosgene ELEMENTS Nitrogen Oxygen Argon Fluorine Chlorine Bromine Iodine Sulfur Mercury HEAT TRANSFER MEDIA Dowtherm A Dowtherm J
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NORMAL PARAFFINS

			Temperature, °C												
			-150	-100	-15	-50	-25	0	20	50	100	150	200	250	300
			Temperature, K												
Substance	Data	Property	123.15	173.15	198.15	223.15	248.15	273.15	293.15	323.15	373.15	423.15	473.15	523.15	573.15
METHANE	Chemical formula: CH ₄	Density, ρ_l (kg/m ³)	409	V	V	V	V	V	V	V	V	V	V	V	V
	Molecular weight: 16.04	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	3.517	V	V	V	V	V	V	V	V	V	V	V	V
	Melting point: −182.49 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	0.175	V	V	V	V	V	V	V	V	V	V	V	V
	Boiling point: -161.73 °C	Dynamic viscosity, η_l (10 ^{−5} Ns/m ²)	8.8	V	V	V	V	V	V	V	V	V	V	V	V
	Critical temperature: −82.6 °C														
	Critical pressure: 4.641 MPa														
ETHANE	Chemical formula: C ₂ H ₆	Density, ρ_l (kg/m ³)	666	561	V	V	V	V	V	V	V	V	V	V	V
	Molecular weight: 30.07	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	2.319	2.403	V	V	V	V	V	V	V	V	V	V	V
	Melting point: −183.27 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	0.199	0.155	V	V	V	V	V	V	V	V	V	V	V
	Boiling point: -88.63 °C	Dynamic viscosity, η_l (10 ^{−5} Ns/m ²)	42.2	22.2	V	V	V	V	V	V	V	V	V	V	V
	Critical temperature: −32.35 °C														
	Critical pressure: 4.913 MPa														
PROPANE	Chemical formula: C ₃ H ₈	Density, ρ_l (kg/m ³)	696	646	619	590	V	V	V	V	V	V	V	V	V
	Molecular weight: 44.10	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	1.959	2.056	2.119	2.202	V	V	V	V	V	V	V	V	V
	Melting point: −187.68 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	0.198	0.164	0.148	(0.133)	V	V	V	V	V	V	V	V	V
	Boiling point: -42.05 °C	Dynamic viscosity, η_l (10 ^{−5} Ns/m ²)	134.1	43.3	30.1	20.0	V	V	V	V	V	V	V	V	V
	Critical temperature: 96.85 °C														
	Critical pressure: 4.264 MPa														
BUTANE	Chemical formula: C ₄ H ₁₀	Density, ρ_l (kg/m ³)	S	698	676	652	627	V	V	V	V	V	V	V	V
	Molecular weight: 58.12	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	2.001	2.052	2.119	2.194	V	V	V	V	V	V	V	V
	Melting point: −138.33 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	0.166	0.153	0.129	0.122	V	V	V	V	V	V	V	V
	Boiling point: −0.49 °C	Dynamic viscosity, η_l (10 ^{−5} Ns/m ²)	S	74.7	49.7	35.5	26.7	V	V	V	V	V	V	V	V
	Critical temperature: 152.01 °C														
	Critical pressure: 3.796 MPa														
PENTANE	Chemical formula: C ₅ H ₁₂	Density, ρ_l (kg/m ³)	S	737	715	693	670	646	626	V	V	V	V	V	V
	Molecular weight: 72.15	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	1.972	2.001	2.060	2.123	2.206	2.273	V	V	V	V	V	V
	Melting point: -129.75 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	0.155	0.151	0.148	0.144	0.140	0.136	V	V	V	V	V	V
	Boiling point: 36.05 °C	Dynamic viscosity, η_l (10 ^{−5} Ns/m ²)	S	125.0	66.0	48.4	36.4	27.7	22.7	V	V	V	V	V	V
	Critical temperature: 196.45 °C														
	Critical pressure: 3.369 MPa														

NORMAL PARAFFINS (Continued)

Substance	Data	Property	Temperature, °C												
			-150	—100	-75	-50	-25	0	20	50	100	150	200	250	300
			Temperature, K												
			123.15	173.15	198.15	223.15	248.15	273.15	293.15	323.15	373.15	423.15	473.15	523.15	573.15
HEXANE	Chemical formula: C_6H_{14}	Density, ρ_l (kg/m ³)	S	S	742	721	700	678	659	631	V	V	V	V	V
	Molecular weight: 86.18	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	1.993	2.035	2.093	2.165	2.227	(2.37)	V	V	V	V	V
	Melting point: —95.32 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	0.156	0.146	0.137	0.127	0.120	0.110	V	V	V	V	V
	Boiling point: 68.73 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	92.0	68.5	51.5	38.3	30.8	22.9	V	V	V	V	V
	Critical temperature: 234.29 °C														
	Critical pressure: 3.031 MPa														
HEPTANE	Chemical formula: C_7H_{16}	Density, ρ_l (kg/m ³)	S	S	761	741	721	701	684	658	V	V	V	V	V
	Molecular weight: 100.20	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	2.104	2.035	2.081	2.144	2.198	2.307	V	V	V	V	V
	Melting point: —90.55 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	0.156	0.148	0.139	0.131	0.124	0.114	V	V	V	V	V
	Boiling point: 98.45 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	129.0	96.6	72.5	52.6	41.3	30.2	V	V	V	V	V
	Critical temperature: 267.46 °C														
	Critical pressure: 2.736 MPa														
OCTANE	Chemical formula: C_8H_{18}	Density, ρ_l (kg/m ³)	S	S	S	757	738	719	703	678	635	V	V	V	V
	Molecular weight: 114.23	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	2.043	2.064	2.131	2.186	2.303	(2.51)	V	V	V	V
	Melting point: —56.8 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	0.152	0.144	0.137	0.131	0.122	0.107	V	V	V	V
	Boiling point: 125.65	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	137.0	102.0	71.4	54.6	38.9	24.4	V	V	V	V
	Critical temperature: 295.65 °C														
	Critical pressure: 2.486 MPa														
NONANE	Chemical formula: C_9H_{20}	Density, ρ_l (kg/m ³)	S	S	S	769	751	733	718	694	653	609	V	V	V
	Molecular weight: 128.26	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	2.047	2.060	2.127	2.177	(2.29)	(2.48)	(2.74)	V	V	V
	Melting point: —53.45 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	0.150	0.142	0.136	0.132	0.124	0.111	0.096	V	V	V
	Boiling point: 150.82 °	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	193.0	143.1	96.4	71.3	49.2	30.1	19.9	V	V	V
	Critical temperature: 321.48 °C														
	Critical pressure: 2.289 MPa														
DECANE	Chemical formula: $C_{10}H_{22}$	Density, ρ_l (kg/m ³)	S	S	S	S	762	745	730	707	667	625	V	V	V
	Molecular weight: 142.29	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	2.085	2.127	2.173	2.265	2.474	(2.71)	V	V	V
	Melting point: -2964° C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	0.143	0.132	0.126	0.117	0.104	0.093	V	V	V
	Boiling point: 174.25	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	200.0	129.2	92.1	61.5	36.4	23.1	V	V	V
	Critical temperature: 344.45 °C														
	Critical pressure: 2.096 MPa														

UNDECANE	Chemical formula: $C_{11}H_{24}$	Density, ρ_l (kg/m ³)	S	S	S	S	772	754	740	718	679	638	V	V	V
	Molecular weight: 156.31	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	2.114	2.123	2.173	(2.29)	(2.45)	(2.67)	V	V	V
	Melting point: -25.55 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	(0.154)	0.146	0.141	0.134	0.124	0.113	V	V	V
	Boiling point: 195.95 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	280.0	171.7	117.6	75.7	43.3	27.9	V	V	V
	Critical temperature: 344.45 °C														
DODECANE	Critical pressure: 1.97 MPa														
	Chemical formula: $C_{12}H_{26}$	Density, ρ_l (kg/m ³)	S	S	S	S	—	756	751	727	689	648	605	V	V
	Molecular weight: 170.34	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	S	2.148	2.173	(2.27)	(2.43)	(2.66)	(2.94)	V	V
	Melting point: -9.55 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	S	0.147	0.143	0.137	0.128	0.118	0.109	V	V
	Boiling point: 216.35 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	226.8	148.9	02.2	51.1	32.3	21.7	V	V
TRIDECANE	Critical temperature: 385.15 °C														
	Critical pressure: 1.82 MPa														
	Chemical formula: $C_{13}H_{28}$	Density, ρ_l (kg/m ³)	S	S	S	S	S	770	756	735	698	658	615	V	V
	Molecular weight: 184.37	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	S	1.971	2.160	(2.27)	(2.43)	(2.64)	(2.91)	V	V
	Melting point: -5.35 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	S	0.148	0.146	0.141	0.132	0.123	0.115	V	V
TETRA-DECANE	Boiling point: 235.45 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	297.6	186.5	111.0	59.5	37.2	24.8	V	V
	Critical temperature: 402.65 °C														
	Critical pressure: 1.72 MPa														
	Chemical formula: $C_{14}H_{30}$	Density, ρ_l (kg/m ³)	S	S	S	S	S	S	763	742	705	666	624	579	V
	Molecular weight: 198.39	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	S	S	2.186	(2.27)	(2.43)	(2.63)	(2.89)	(3.26)	
PENTA-DECANE	Melting point: 5.85 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	S	S	0.145	0.140	0.130	0.120	0.102	0.093	
	Boiling point: 253.55 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	S	231.9	132.4	70.1	43.1	28.7	20.8	V
	Critical temperature: 420.85 °C														
	Critical pressure: 1.62 MPa														
	Chemical formula: $C_{15}H_{32}$	Density, ρ_l (kg/m ³)	S	S	S	S	S	S	768	748	712	673	631	V	V
HEXA-DECANE	Molecular weight: 212.42	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	S	S	2.151	(2.27)	(2.43)	(2.62)	(2.86)	V	V
	Melting point: 9.85 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	S	S	0.141	0.135	0.125	0.115	0.105	V	V
	Boiling point: 207.65 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	S	286.3	156.7	78.7	47.9	31.6	V	V
	Critical temperature: 433.85 °C														
	Critical pressure: 1.52 MPa														
HEXA-DECANE	Chemical formula: $C_{16}H_{34}$	Density, ρ_l (kg/m ³)	S	S	S	S	S	S	775	753	717	679	638	594	V
	Molecular weight: 226.45	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	S	S	2.144	2.272	(2.43)	(2.62)	(2.86)	(3.18)	V
	Melting point: 17.85 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	S	S	0.150	0.144	0.134	0.124	0.108	0.099	V
	Boiling point: 286.85 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	S	350.6	184.1	89.5	53.6	35.2	(25.3)	V
	Critical temperature: 443.85 °C														
HEXA-DECANE	Critical pressure: 1.42 MPa														

NORMAL PARAFFINS (Continued)

		Temperature, °C													
		Temperature, K													
Substance	Data	Property	123.15	173.15	198.15	223.15	248.15	273.15	293.15	323.15	373.15	423.15	473.15	523.15	573.15
HEPTA- DECANE	Chemical formula: $C_{17}H_{36}$	Density, ρ_l (kg/m ³)	S	S	S	S	S	S	S	758	722	684	644	600	555
	Molecular weight: 240.47	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	S	S	S	2.274	2.427	(2.61)	(2.85)	(3.16)	(3.60)
	Melting point: 21.85 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	S	S	S	0.139	0.129	0.120	0.111	0.102	0.094
	Boiling point: 302.5 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	S	S	214.4	101.1	59.7	39.0	27.2	19.9
	Critical temperature: 459.85 °C														
OCTA- DECANE	Chemical formula: $C_{18}H_{38}$	Density, ρ_l (kg/m ³)	S	S	S	S	S	S	S	762	727	689	649	606	561
	Molecular weight: 254.50	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	S	S	S	2.276	2.428	(2.61)	(2.84)	(3.14)	(3.56)
	Melting point: 28.15 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	S	S	S	0.141	0.132	0.122	0.113	0.105	0.096
	Boiling point: 316.25 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	S	S	248.5	113.5	66.2	43.1	30.1	21.9
	Critical temperature: 471.85 °C														
NONA- DECANE	Chemical formula: $C_{19}H_{40}$	Density, ρ_l (kg/m ³)	S	S	S	S	S	S	S	766	731	694	654	612	567
	Molecular weight: 268.52	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	S	S	S	(2.28)	(2.43)	(2.61)	(2.83)	(3.12)	(3.50)
	Melting point: 31.85 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	S	S	S	0.143	0.134	0.125	0.116	0.107	0.099
	Boiling point: 329.95 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	S	S	286.1	126.7	73.1	47.2	32.2	23.5
	Critical temperature: 482.85 °C														
EICO- SANE	Chemical formula: $C_{20}H_{42}$	Density, ρ_l (kg/m ³)	S	S	S	S	S	S	S	769	742	698	659	617	572
	Molecular weight: 282.56	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	S	S	S	(2.28)	(2.43)	(2.61)	(2.83)	(3.11)	(3.47)
	Melting point: 36.85 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	S	S	S	0.145	0.136	0.127	0.118	0.109	0.101
	Boiling point: 343.85 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	S	S	327.6	140.8	80.1	51.5	34.6	25.2
	Critical temperature: 493.85 °C														
	Critical pressure: 1.11 MPa														

ISOPARAFFINS

Substance	Data	Property	Temperature, °C												
			-150	-100	-75	-50	-25	0	20	50	100	150	200	250	300
			Temperature, K												
			123.15	173.15	198.15	223.15	248.15	273.15	293.15	323.15	373.15	423.15	473.15	523.15	573.15
2-METHYL-PROPANE	Chemical formula: C_4H_{10}	Density, ρ_l (kg/m ³)	724	680	659	634	609	V	V	V	V	V	V	V	V
	Molecular weight: 58.12	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	1.729	1.884	1.968	2.060	2.177	V	V	V	V	V	V	V	V
	Melting point: -159.55 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	0.182	0.155	0.143	0.130	0.118	V	V	V	V	V	V	V	V
	Boiling point: -11.75 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	1100	112	61.7	39.1	28.3	V	V	V	V	V	V	V	V
	Critical temperature: 134.95 °C														
2-METHYL-BUTANE	Critical pressure: 3.65 MPa														
	Chemical formula: C_5H_{12}	Density, ρ_l (kg/m ³)	(760)	727	706	687	663	639	620	V	V	V	V	V	V
	Molecular weight: 72.15	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	1.725	1.838	1.905	1.980	2.068	2.169	2.265	V	V	V	V	V	V
	Melting point: -159.90 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	0.182	0.159	0.148	0.137	0.127	0.117	0.110	V	V	V	V	V	V
	Boiling point: 27.85 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	1720	154	84.4	55.0	37.8	27.9	22.5	V	V	V	V	V	V
2-METHYL-PENTANE	Critical temperature: 187.25 °C														
	Critical pressure: 3.38 MPa														
	Chemical formula: C_6H_{14}	Density, ρ_l (kg/m ³)	(779)	(752)	(734)	(714)	(693)	672	653	625	V	V	V	V	V
	Molecular weight: 86.18	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	1.712	1.813	1.884	1.955	2.043	2.139	2.227	(2.39)	V	V	V	V	V
	Melting point: -153.65 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	(0.180)	0.160	0.151	0.140	0.132	0.122	0.115	0.103	V	V	V	V	V
3-METHYL-PENTANE	Boiling point: 60.25 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	2820	204	110	68.1	48.0	37.0	30.0	22.5	V	V	V	V	V
	Critical temperature: 224.35 °C														
	Critical pressure: 3.01 MPa														
	Chemical formula: C_6H_{14}	Density, ρ_l (kg/m ³)	S	(763)	(751)	725	705	683	665	637	V	V	V	V	V
	Molecular weight: 86.18	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	1.800	1.859	1.926	2.010	2.131	2.190	(2.34)	V	V	V	V	V
2,2-DIMETHYL-PROPANE	Melting point: -118.15 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	0.159	0.149	0.140	0.131	0.122	0.115	0.105	V	V	V	V	V
	Boiling point: 63.25 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	(95)	(76)	(61)	(46)	39.4	32.4	25.3	V	V	V	V	V
	Critical temperature: 231.25 °C														
	Critical pressure: 3.12 MPa														
	Chemical formula: C_5H_{12}	Density, ρ_l (kg/m ³)	S	S	S	S	S	615	V	V	V	V	V	V	V
2,2-DIMETHYL-PROPANE	Molecular weight: 72.15	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	S	2.19	V	V	V	V	V	V	V
	Melting point: -16.57 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	S	0.105	V	V	V	V	V	V	V
	Boiling point: 9.5 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	32.9	V	V	V	V	V	V	V
	Critical temperature: 160.63 °C														
	Critical pressure: 3.196 MPa														

ISOPARAFFINS (Continued)

			Temperature, °C												
			-150	-100	-75	-50	-25	0	20	50	100	150	200	250	300
			Temperature, K												
Substance	Data	Property	123.15	173.15	198.15	223.15	248.15	273.15	293.15	323.15	373.15	423.15	473.15	523.15	573.15
2,2-DIMETHYL-BUTANE	Chemical formula: C₆H₁₄	Density, ρ_l(kg/m³)	S	S	(737)	(714)	(690)	665	647	(639)	V	V	V	V	V
	Molecular weight: 86.18	Specific heat capacity, c_{p,l} (kJ/kg K)	S	S	1.809	1.892	1.976	2.081	2.169	(2.31)	V	V	V	V	V
	Melting point: -99.85 °C	Thermal conductivity, λ_l [(W/m²)/(K/m)]	S	S	0.138	0.129	0.120	0.112	0.106	0.095	v	V	V	V	V
	Boiling point: 49.75 °C	Dynamic viscosity, η_l (10⁻⁵ Ns/m²)	S	S	—	(100)	(67)	47.8	37.6	(31)	v	v	V	V	V
	Critical temperature: 215.55°C														
2,3-DIMETHYL-BUTANE	Critical pressure: 3.08 MPa														
	Chemical formula: C₆H₁₄	Density, ρ_l(kg/m³)	S	(759)	(741)	(722)	(701)	681	663	635	V	V	V	V	V
	Molecular weight: 86.18	Specific heat capacity, c_{p,l} (kJ/kg K)	S	1.754	1.821	1.901	1.985	2.077	2.165	(2.35)	V	V	V	V	V
	Melting point: -128.55 °C	Thermal conductivity, A_l [(W/m²)/(K/m)]	S	0.148	0.139	0.130	0.121	0.113	0.107	0.099	v	V	V	V	V
	Boiling point: 58.05 °C	Dynamic viscosity, η_l (10⁻⁵ Ns/m²)	S	(152)	(114)	(86)	(65)	49.5	38.5	27.6	V	V	V	V	V
	Critical temperature: 225.85°C														
	Critical pressure: 3.13 MPa														

OLEFINS

			Temperature, °C												
			-150	-100	-75	-50	-25	0	20	50	100	150	200	250	300
			Temperature, K												
Substance	Data	Property	123.15	173.15	198.15	223.15	248.15	273.15	293.15	323.15	373.15	423.15	473.15	523.15	573.15
ETHYLENE	Chemical formula: C₂H₄	Density, ρ_l (kg/m ³)	630	V	V	V	V	V	V	V	V	V	V	V	V
	Molecular weight: 28.05	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	2.433	V	V	V	V	V	V	V	V	V	V	V	V
	Melting point: -169.15 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	0.242	V	V	V	V	V	V	V	V	V	V	V	V
	Boiling point: -103.72 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	41.0	V	V	V	V	V	V	V	V	V	V	V	V
	Critical temperature: 9.5 °C														
	Critical pressure: 5.06 MPa														
PROPYLENE	Chemical formula: C₃H₆	Density, ρ_l (kg/m ³)	729	671	641	612	V	V	V	V	V	V	V	V	V
	Molecular weight: 42.08	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	2.098	2.085	2.123	2.117	V	V	V	V	V	V	V	V	V
	Melting point: -185.25 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	0.217	0.179	0.160	0.145	V	V	V	V	V	V	V	V	V
	Boiling point: -47.7 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	129.1	37.0	26.5	19.2	V	V	V	V	V	V	V	V	V
	Critical temperature: 91.65 °C														
	Critical pressure: 4.61 MPa														
BUTENE-1	Chemical formula: C₄H₈	Density, ρ_l (kg/m ³)	(755)	712	691	668	645	V	V	V	V	V	V	V	V
	Molecular weight: 56.11	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	1.888	1.909	1.959	2.022	2.102	V	V	V	V	V	V	V	V
	Melting point: -185.35 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	0.204	0.175	0.161	0.147	0.135	V	V	V	V	V	V	V	V
	Boiling point: -6.25 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	242	64.0	42.0	30.0	22.5	V	V	V	V	V	V	V	V
	Critical temperature: -146.4 °C														
	Critical pressure: 4.02 MPa														
PENTENE-1	Chemical formula: C₅H₁₀	Density, ρ_l (kg/m ³)	(800)	755	734	711	687	662	642	V	V	V	V	V	V
	Molecular weight: 70.13	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	(1.84)	1.859	1.901	1.955	2.026	2.119	2.219	V	V	V	V	V	V
	Melting point: -165.25 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	0.196	0.172	0.160	0.149	0.138	0.127	0.119	V	V	V	V	V	V
	Boiling point: 29.95 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	56.9	99.1	64.0	43.1	31.0	24.0	20.9	V	V	V	V	V	V
	Critical temperature: 191.55 °C														
	Critical pressure: 4.05 MPa														
HEXENE-1	Chemical formula: C₆H₁₂	Density, ρ_l (kg/m ³)	S	770	750	732	713	693	673	645	V	V	V	V	V
	Molecular weight: 84.16	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	1.857	1.882	1.941	2.004	2.090	2.161	(2.28)	V	V	V	V	V
	Melting point: -139.85 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	0.169	0.159	0.149	0.139	0.130	0.122	0.112	V	V	V	V	V
	Boiling point: 63.45 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	166	94	63.1	44.0	33.0	28.0	23.0	V	V	V	V	V
	Critical temperature: 230.85 °C														
	Critical pressure: 3.17 MPa														

			-150	-100	-75	-50	-25	0	Temperature, °C		100	150	200	250	300
									20	50					
Substance	Data	Property	123.15	173.15	198.15	223.15	248.15	273.15	293.15	323.15	373.15	423.15	473.15	523.15	573.15
HEPTENE-1	Chemical formula: C ₇ H ₁₄	Density, ρ _t (kg/m*)	S	(788)	(770)	(752)	(733)	713	697	671	V	V	V	V	V
	Molecular weight: 98.195	Specific heat capacity,													
	Melting point: −118.85 °C	c _{p,t} (kJ/kg K)	S	1.842	1.880	1.922	1.989	2.072	2.148	(2.26)	V	V	V	V	V
	Boiling point: 93.65 °C	Thermal conductivity,													
	Critical temperature:	λ _t [(W/m²)/(K/m)]	S	0.167	0.158	0.149	0.140	0.132	0.125	0.115	V	V	V	V	V
	264.05 °C	Dynamic viscosity,													
	Critical pressure: 2.84 MPa	η _t (10 ^{−5} Ns/m²)	S	296	150	89.4	61	44.0	35.0	27.0	V	V	V	V	V
OCTENE-1	Chemical formula: C ₈ H ₁₆	Density, ρ _t (kg/m³)	S	S	S	(773)	(744)	732	715	689	(646)	V	V	V	V
	Molecular weight: 112.21	Specific heat capacity,													
	Melting point: −101.7 °C	c _{p,t} (kJ/kg K)	S	S	S	1.943	1.992	2.067	2.129	(2.24)	(2.45)	V	V	V	V
	Boiling point: 121.3 °C	Thermal conductivity,													
	Critical temperature:	λ _t [(W/m²)/(K/m)]	S	S	S	0.150	0.142	0.134	0.128	0.119	0.105	V	V	V	V
	293.5 °C	Dynamic viscosity,													
	Critical pressure: 2.53 MPa	η _t (10 ^{−5} Ns/m²)	S	S	S	133	86	61.3	47.0	34.7	23.4	V	V	V	V
PROPA-DIENE	Chemical formula: C ₃ H ₄	Density, ρ _t (kg/m)	S	(791)	(712)	682	V	V	V	V	V	V	V	V	V
	Molecular weight: 40.06	Specific heat capacity,													
	Melting point: −136.25 °C	c _{p,t} (kJ/kg K)	S	(1.87)	(1.94)	(2.02)	V	V	V	V	V	V	V	V	V
	Boiling point: -34.45 °C	Thermal conductivity,													
	Critical temperature:	λ _t [(W/m²)/(K/m)]	S	(0.206)	(0.187)	(0.170)	V	V	V	V	V	V	V	V	V
	119.85 °C	Dynamic viscosity,													
	Critical pressure: 5.47 MPa	η _t (10 ^{−5} Ns/m²)	S	(46)	(32)	(23)	V	V	V	V	V	V	V	V	V
BUTADIENE (1,2)	Chemical formula: C ₄ H ₆	Density, ρ _t (kg/m)	S	(785)	(760)	(730)	(704)	(676)	V	V	V	V	V	V	V
	Molecular weight: 54.09	Specific heat capacity,													
	Melting point: −136.15 °C	c _{p,t} (kJ/kg K)	S	2.035	2.041	2.086	2.136	2.208	V	V	V	V	V	V	V
	Boiling point: 10.85 °C	Thermal conductivity,													
	Critical temperature:	λ _t [(W/m²)/(K/m)]	S	(0.196)	(0.181)	(0.167)	(0.153)	(0.140)	v	V	V	V	V	V	V
	170.55 °C	Dynamic viscosity,													
	Critical pressure: 4.50 MPa	η _t (10 ^{−5} Ns/m²)	S	(75)	(50)	(36)	(27)	(22)	V	V	V	V	V	V	V
BUTADIENE (1,3)	Chemical formula: C ₄ H ₆	Density, ρ _t (kg/m³)	S	755	728	701	673	V	V	V	V	V	V	V	V
	Molecular weight: 54.09	Specific heat capacity,													
	Melting point: −108.91 °C	c _{p,t} (kJ/kg K)	S	2.002	2.068	2.171	2.217	V	V	V	V	V	V	V	V
	Boiling point: −4.46 °C	Thermal conductivity,													
	Critical temperature:	λ _t [(W/m²)/(K/m)]	S	0.190	0.175	0.161	0.147	V	V	V	V	V	V	V	V
	152.0 °C	Dynamic viscosity,													
	Critical pressure: 4.33 MPa	η _t (10 ^{−5} Ns/m²)	S	(72)	(48)	(34)	(26)	V	V						

PENTA-DIENE (1,2) PENTA-DIENE (1,trans 3) PENTA-DIENE (1,4) PENTA-DIENE (2,3)	Chemical formula: C_5H_8 Molecular weight: 68.12 Melting point: -137.25 °C Boiling point: 44.85 °C Critical temperature: 229.85 °C Critical pressure: 4.07 MPa	Density, ρ_l (kg/m*) Specific heat capacity, $c_{p,l}$ (kJ/kg K) Thermal conductivity, λ_l [(W/m ²)/(K/m)] Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S S S S	(801) 1.934 (0.174) (115)	(778) 1.960 (0.163) (72)	(755) 2.002 (0.152) (48)	(733) 2.059 (0.141) (36)	(710) 2.132 (0.131) (27)	621 2.20 (0.123) (22)	V v V V	V V V V	V V V V	V V V V	V V V V
	Chemical formula: C_5H_8 Molecular weight: 68.12 Melting point: -87.45 °C Boiling point: 42.05 °C Critical temperature: 222.85 °C Critical pressure 3.99 MPa	Density, ρ_l (kg/m ³) Specific heat capacity, $c_{p,l}$ (kJ/kg K) Thermal conductivity, λ_l [(W/m ²)/(K/m)] Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S S S S	S S S S	(763) 1.919 (0.163) (72)	(740) 1.953 (0.152) (48)	(718) 2.009 (0.141) (36)	(695) 2.089 (0.131) (27)	676 2.169 (0.123) (22)	V V V V	V V V V	V V V V	V V V V	V V V V
	Chemical formula: C_5H_8 Molecular weight: 68.12 Melting point: -148.5 °C Boiling point: 25.95 °C Critical temperature: 187° C Critical pressure: 3.62 MPa	Density, ρ_l (kg/m*) Specific heat capacity, $c_{p,l}$ (kJ/kg K) Thermal conductivity, λ_l [(W/m ²)/(K/m)] Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S S S S	(783) 1.863 (0.174) (115)	(758) 1.880 (0.163) (72)	(733) 1.926 (0.152) (48)	(708) 1.993 (0.141) (36)	(683) 2.085 (0.131) (27)	660 2.165 (0.123) (22)	V V V V	V V V V	V V V V	V V V V	V V V V
	Chemical formula: C_5H_8 Molecular weight: 68.12 Melting point: -125.7 °C Boiling point: 48.2 °C Critical temperature: 226 °C Critical pressure: 41.97 MPa	Density, ρ_l (kg/m*) Specific heat capacity, $c_{p,l}$ (kJ/kg K) Thermal conductivity, λ_l [(W/m ²)/(K/m)] Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S S S S	(807) 1.999 (0.174) (115)	(783) 2.019 (0.163) (72)	(759) 2.052 (0.152) (48)	(736) 2.100 (0.141) (36)	(713) 2.162 (0.131) (27)	695 2.221 (0.112) (22)	V v v V	V V V V	V V V V	V V V V	V V V V

ACETYLENES

Substance	Data	Property	Temperature, °C												
			-150	-100	-75	-50	-25	0	20	50	100	150	200	250	300
			Temperature, K												
			123.15	173.15	198.15	223.15	248.15	273.15	293.15	323.15	373.15	423.15	473.15	523.15	573.15
ACETYLENE	Chemical formula: C_2H_2	Density, ρ_l (kg/m ³)	S	S	612	V	V	V	V	V	V	V	V	V	V
	Molecular weight: 26.04	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	(3.1)	v	v	V	V	V	V	V	V	V	V
	Melting point: -80.75 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	(0.54)	v	v	V	V	V	V	V	V	V	V
	Boiling point: -83.95 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	(16)	V	V	V	V	V	V	V	V	V	V
	Critical temperature: 35.55 °C														
METHYL-ACETYLENE	Chemical formula: C_3H_4	Density, ρ_l (kg/m ³)	S	(770)	(740)	710	673	V	V	V	V	V	V	V	V
	Molecular weight: 40.06	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	(2.17)	(2.24)	(2.32)	(2.42)	V	V	V	V	V	V	V	V
	Melting point: -102.65 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	(0.19)	(0.175)	(0.16)	(0.145)	V	V	V	V	V	V	V	V
	Boiling point: -23.15 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	(44)	(31)	(24)	(19)	V	V	V	V	V	V	V	V
	Critical temperature: 129.25 °C														
ETHYL-ACETYLENE	Chemical formula: C_4H_6	Density, ρ_l (kg/m ³)	S	(780)	(755)	(730)	705	678	V	V	V	V	V	V	V
	Molecular weight: 54.09	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	2.125	2.158	2.218	2.300	2.398	V	V	V	V	V	V	V
	Melting point: -130° C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	(0.226)	(0.197)	(0.172)	(0.151)	(0.133)	v	V	V	V	V	V	V
	Boiling point: 8.7 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S		(53)	(40)	(35)	(24)	V	V	V	V	V	V	V
	Critical temperature: 190.5 °C														
DIMETHYL-ACETYLENE	Chemical formula: C_4H_6	Density, ρ_l (kg/m ³)	S	S	S	S	(742)	(715)	691	V	V	V	V	V	V
	Molecular weight: 54.09	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	2.190	2.257	2.311	V	V	V	V	V	V
	Melting point: -32.3 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	(0.167)	(0.146)	(0.133)	V	V	V	V	V	V
	Boiling point: 27.2 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	(35)	(27)	(23)	V	V	V	V	V	V
	Critical temperature: 212° C														
	Critical pressure: 5.13 MPa														

NAPHTHENES

Substance	Data	Property	Temperature, °C												
			-150	-100	-75	-50	-25	0	20	50	100	150	200	250	300
			Temperature, K												
			123.15	173.15	198.15	223.15	248.15	273.15	293.15	323.15	373.15	423.15	473.15	523.15	573.15
CYCLO-PROPANE	Chemical formula: C_3H_6	Density, ρ_l (kg/m ³)	S	740	716	693	V	V	V	V	V	V	V	V	V
	Molecular weight: 42.08	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	1.779	1.809	1.863	V	V	V	V	V	V	V	V	V
	Melting point: -127.45 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	(0.166)	(0.145)	V	V	V	V	V	V	V	V	V
	Boiling point: -32.75 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	(40)	(30)	V	V	V	V	V	V	V	V	V
	Critical temperature: 124.65 °C														
CYCLO-BUTANE	Critical pressure: 5.49 MPa														
	Chemical formula: C_4H_8	Density, ρ_l (kg/m ³)	S	S	791	769	747	724	V	V	V	V	V	V	V
	Molecular weight: 56.11	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	1.617	1.688	1.756	1.842	V	V	V	V	V	V	V
	Melting point: -90.75 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	(0.171)	(0.154)	(0.140)	(0.127)	V	V	V	V	V	V	V
	Boiling point: 12.55 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	(60)	(45)	(34)	(26)	V	V	V	V	V	V	V
CYCLO-PENTANE	Critical temperature: 186.75 °C														
	Critical pressure: 4.99 MPa														
	Chemical formula: C_5H_{10}	Density, ρ_l (kg/m ³)	S	S	(825)	(810)	(790)	765	745	V	V	V	V	V	V
	Molecular weight: 70.13	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	1.444	1.507	1.591	1.696	1.800	V	V	V	V	V	V
	Melting point: -93.9 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	0.165	0.156	0.148	0.139	0.133	V	V	V	V	V	V
METHYL-CYCLO-PENTANE	Boiling point: 49.3 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	(135)	(105)	78.1	55.5	43.8	V	V	V	V	V	V
	Critical temperature: 238.65 °C														
	Critical pressure: 4.508 MPa														
	Chemical formula: C_6H_{12}	Density, ρ_l (kg/m ³)	S	(855)	(833)	(811)	(789)	767	749	720	V	V	V	V	V
	Molecular weight: 84.16	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	1.516	1.545	1.612	1.696	1.719	1.863	(2.01)	V	V	V	V	V
ETHYL-CYCLO-PENTANE	Melting point: -142.45 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	0.157	0.149	0.142	0.135	0.129	0.123	0.111	V	V	V	V	V
	Boiling point: 7 1.85 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	(300)	(190)	(130)	93.1	65.0	50.7	36.5	V	V	V	V	V
	Critical temperature: 259.55 °C														
	Critical pressure: 3.79 MPa														
	Chemical formula: C_7H_{14}	Density, ρ_l (kg/m ³)	S	(863)	(843)	(823)	(803)	(783)	763	739	691	V	V	V	V
ETHYL-CYCLO-PENTANE	Molecular weight: 98.19	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	1.521	1.569	1.630	1.701	1.110	1.873	(2.01)	(2.22)	V	V	V	V
	Melting point: -138.45 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	(0.155)	(0.148)	(0.141)	(0.134)	(0.127)	(0.122)	(0.114)	(0.102)	V	V	V	V
	Boiling point: 103.45 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S		—	(150)	(101)	12.4	56.7	41.2	27.0	V	V	V	V
	Critical temperature: 296.35 °C														
	Critical pressure: 3.39 MPa														

NAPHTHENES (Continued)

Substance	Data	Property	Temperature, °C												
			-150	-100	-75	-50	-25	0	20	50	100	150	200	250	300
			Temperature, K												
			123.15	173.15	198.15	223.15	248.15	273.15	293.15	323.15	373.15	423.15	473.15	523.15	573.15
PROPYG- CYCLO- PENTANE	Chemical formula: C_8H_{16}	Density, ρ_l (kg/m ³)	S	(864)	(846)	(828)	810	792	777	752	710	v	V	V	V
	Molecular weight: 112.22	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	(1.48)	(1.57)	(1.66)	1.749	1.840	1.915	2.031	2.331	V	V	V	V
	Melting point: -117.35 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	(0.155)	(0.149)	(0.143)	(0.137)	(0.132)	(0.127)	(0.121)	(0.109)	V	V	V	V
	Boiling point: 130.95 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	—	—	(215)	140	89.8	68.3	48.8	33.0	v	V	V	V
	Critical temperature: 329.85 °C														
BUTYL- CYCLO- PENTANE	Critical pressure: 3.00 MPa														
	Chemical formula: C_9H_{18}	Density, ρ_l (kg/m ³)	S	(867)	(850)	(833)	816	799	784	762	723	(681)	v	v	V
	Molecular weight: 126.25	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	1.446	1.480	1.528	1.592	1.664	1.732	1.840	2.026	(2.22)	V	V	V
	Melting point: -108.2 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	(0.152)	(0.144)	(0.139)	(0.134)	(0.128)	(0.125)	(0.118)	(0.108)	(0.098)	V	V	V
	Boiling point: 156.8 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S		—	(260)	(175)	120.7	89.0	60.8	38.0	(26)	V	V	V
PENTY- CYCLO- PENTANE	Critical temperature: 343.5 °C														
	Critical pressure: 2.58 MPa														
	Chemical formula: $C_{10}H_{20}$	Density, ρ_l (kg/m ³)	S	S	(862)	(844)	(825)	(807)	791	(770)	(733)	(695)	V	V	V
	Molecular weight: 140.28	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	—	—	(1.62)	(1.69)	(1.76)	(1.86)	(2.05)	(2.25)	V	V	V
	Melting point: (-92) °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	(0.146)	(0.141)	(0.136)	(0.131)	(0.127)	(0.121)	(0.111)	(0.101)	V	V	V
HEXYL- CYCLO- PENTANE	Boiling point: 180.0 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	—	(430)	255	163.1	115.5	75.3	45.0	(30)	v	v	V
	Critical temperature: 366 °C														
	Critical pressure: 2.37 MPa														
	Chemical formula: $C_{11}H_{22}$	Density, ρ_l (kg/m ³)	S	S	(866)	(848)	(830)	(813)	797	(778)	(742)	(705)	(665)	V	V
	Molecular weight: 154.30	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	—	—	(1.66)	(1.72)	(1.78)	(1.88)	(2.06)	(2.25)	(2.45)	V	V
CYCLO- HEXANE	Melting point: (-79) °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	(0.147)	(0.142)	(0.137)	(0.132)	(0.127)	(0.123)	(0.113)	(0.104)	(0.095)	V	V
	Boiling point: 203.15 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	—	(560)	350	215.1	149.4	93.8	54.0	(33)	—	v	V
	Critical temperature: 386.95 °C														
	Critical pressure: 2.14 MPa														
	Chemical formula: C_6H_{12}	Density, ρ_l (kg/m ³)	S	S	S	S	S	S	779	750	v	V	V	V	V
CYCLO- HEXANE	Molecular weight: 84.16	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	S	S	2.081	2.119	V	V	V	V	V
	Melting point: 6.55 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	S	S	0.120	0.113	v	V	V	V	V
	Boiling point: 80.72 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	S	98.0	60.6	v	V	V	V	V
	Critical temperature: 281.0 °C														
	Critical pressure: 4.075 MPa														

METHYL- CYCLO- HEXANE	Chemical formula: C_7H_{14}	Density, ρ_l (kg/m ³)	S	870	850	828	808	787	769	742	697	V	V	V	V
	Molecular weight: 98.19	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	1.470	1.537	1.608	1.687	1.779	1.863	(1.97)	(2.23)	V	V	V	V
	Melting point: -126.55 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	0.135	0.130	0.125	0.121	0.116	0.112	0.107	0.098	V	V	V	V
	Boiling point: 100.95 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	(600)	(360)	(235)	155.0	99.3	13.5	50.0	30.0	v	V	V	V
ETHYL- CYCLO- HEXANE	Critical temperature: 298.95 °C														
	Critical pressure: 3.48 MPa														
	Chemical formula: C_8H_{16}	Density, ρ_l (kg/m ³)	S	(876)	(858)	(840)	(822)	(803)	787	(780)	(722)	V	V	V	V
	Molecular weight: 112.22	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	1.470	1.537	1.604	1.691	1.779	1.863	(1.98)	(2.22)	V	V	V	V
ISOPROPYL- CYCLO- HEXANE	Melting point: -111.35 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	(0.128)	(0.124)	(0.120)	(0.117)	(0.114)	(0.111)	(0.107)	(0.100)	v	V	V	V
	Boiling point: 13 1.75 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S		(450)	(290)	180.0	114.2	84.2	58.2	37.0	v	V	V	V
	Critical temperature: 335.85 °C														
	Critical pressure: 3.03 MPa														
BUTYL- CYCLO- HEXANE	Chemical formula: C_9H_{18}	Density, ρ_l (kg/m ³)	S	S	(876)	(856)	(837)	817	803	(778)	(739)	(699)	V	V	V
	Molecular weight: 126.24	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	(1.56)	(1.63)	(1.70)	(1.79)	(1.86)	(1.99)	(2.21)	(2.49)	V	V	V
	Melting point: -89.75 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	(0.115)	(0.112)	(0.109)	(0.106)	(0.104)	(0.101)	(0.096)	(0.090)	V	V	V
	Boiling point: 154.55 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	(400)	235.1	140.8	100.6	61.2	42.0	(29)	V	V	V
PENTYL- CYCLO- HEXANE	Critical temperature: 366.85 °C														
	Critical pressure: 2.84 MPa														
	Chemical formula: $C_{10}H_{20}$	Density, ρ_l (kg/m ³)	S	S	S	(860)	(843)	(825)	811	(790)	(754)	(718)	V	V	V
	Molecular weight: 140.27	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	1.630	1.695	1.778	1.897	1.960	2.160	2.37	V	V	V
HEXYL- CYCLO- HEXANE	Melting point: -74.75 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	(0.117)	(0.114)	(0.112)	(0.109)	(0.107)	0.101	(0.096)	V	V	V
	Boiling point: 180.95 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	(500)	(310)	191.0	131.4	83.1	50.1	(30)	V	V	V
	Critical temperature: 415.1 °C														
	Critical pressure: 2.41 MPa														
PENTYL- CYCLO- HEXANE	Chemical formula: $C_{11}H_{22}$	Density, ρ_l (kg/m ³)	S	S	S	(855)	(837)	(819)	805	(783)	(746)	(708)	(670)	V	V
	Molecular weight: 154.30	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	(1.68)	(1.75)	(1.84)	(1.92)	(2.04)	(2.25)	—	—	V	V
	Melting point: -57.5 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	(0.116)	(0.113)	(0.111)	(0.109)	(0.106)	(0.101)	(0.095)	(0.090)	V	V
	Boiling point: 202.8 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	(850)	(470)	264.1	172.3	102.7	57.0	(31)	—	v	V
HEXYL- CYCLO- HEXANE	Critical temperature: 394° C														
	Critical pressure: 2.21 MPa														
	Chemical formula: $C_{12}H_{24}$	Density, ρ_l (kg/m ³)	S	S	S	S	(838)	(825)	810	(790)	(755)	(718)	(681)	v	V
	Molecular weight: 168.34	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	(1.77)	(1.85)	(1.93)	(2.05)	(2.25)	—	—	V	V
HEXYL- CYCLO- HEXANE	Melting point: (-40) °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	(0.115)	(0.113)	(0.110)	(0.107)	(0.101)	(0.096)	(0.091)	V	V
	Boiling point: (228) °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	(620)	352.1	222.0	126.8	66.0	(34)	—	v	V
	Critical temperature: 412° C														
	Critical pressure: 2.04 MPa														

NAPHTHENES (Continued)

			Temperature, °C												
			-150	-100	-75	-50	-25	0	20	50	100	150	200	250	300
			Temperature, K												
Substance	Data	Property	123.15	173.15	198.15	223.15	248.15	273.15	293.15	323.15	373.15	423.15	473.15	523.15	573.15
CYCLO-PENTENE	Chemical formula: C₅H₈	Density, ρ_l(kg/m³)	S	(892)	(867)	(842)	(817)	792	770	V	V	V	V	V	V
	Molecular weight: 68.12	Specific heat capacity, c_{p,l} (kJ/kg K)	S	1.453	1.470	1.532	1.608	1.696	1.779	V	V	V	V	V	V
	Melting point: −135.05 °C	Thermal conductivity, λ_l [(W/m²)/(K/m)]	S	0.181	0.173	0.165	0.158	0.150	0.145	V	V	V	V	V	V
	Boiling point: 44.25 °C	Dynamic viscosity, η_l (10^{−5} Ns/m²)	S		—	(75)	(56)	43.6	34.7	V	V	V	V	V	V
	Critical temperature: 232.85 °C														
CYCLO-HEXENE	Critical pressure: 4.97 MPa														
	Chemical formula: C₆H₁₀	Density, ρ_l(kg/m³)	S	(925)	(900)	(875)	852	830	811	780	V	V	V	V	V
	Molecular weight: 82.15	Specific heat capacity, c_{p,l} (kJ/kg K)	S	1.419	1.478	1.537	1.616	1.708	1.792	(1.91)	V	V	V	V	V
	Melting point: -103.45 °C	Thermal conductivity, λ_l [(W/m²)/(K/m)]	S	0.158	0.154	0.149	0.145	0.140	0.134	0.125	V	V	V	V	V
	Boiling point: 82.95 °C	Dynamic viscosity, η_l (10^{−5} Ns/m²)	S												
	Critical temperature: 287.25 °C														
	Critical pressure: 4.35 MPa														

AROMATICS

			- 150	- 100	- 75	- 50	- 25	0	Temperature, °C		100	150	200	250	300
			Temperature, K												
Substance	Data	Property	123.15	173.15	198.15	223.15	248.15	273.15	293.15	323.15	373.15	423.15	473.15	523.15	573.15
BENZENE	Chemical formula: C ₆ H ₆	Density, ρ _l (kg/m ³)	S	S	S	S	S	S	879	847	V	V	V	V	V
	Molecular weight: 78.11	Specific heat capacity, c _{p,l} (kJ/kg K)	S	S	S	S	S	S	1.729	1.821	V	V	V	V	V
	Melting point: 5.55 °C	Thermal conductivity, λ _l [(W/m ²)/(K/m)]	S	S	S	S	S	S	0.144	0.134	V	V	V	V	V
	Boiling point: 80.11 °C	Dynamic viscosity, η _l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	S	64.9	43.6	V	V	V	V	V
	Critical temperature: 289.45 °C														
	Critical pressure: 4.924 MPa														
TOLUENE	Chemical formula: C ₇ H ₈	Density, ρ _l (kg/m ³)	S	S	955	932	908	885	867	839	793	V	V	V	V
	Molecular weight: 92.14	Specific heat capacity, c _{p,l} (kJ/kg K)	S	S	1.465	1.507	1.553	1.612	1.717	1.800	1.968	V	V	V	V
	Melting point: -94.99 °C	Thermal conductivity, λ _l [(W/m ²)/(K/m)]	S	S	0.156	0.152	0.148	0.144	0.141	0.136	0.128	V	V	V	V
	Boiling point: 110.63 °C	Dynamic viscosity, η _l (10 ⁻⁵ Ns/m ²)	S	S	500	212	117.0	77.3	58.6	41.9	26.9	V	V	V	V
	Critical temperature: 320.85 °C														
	Critical pressure: 4.05 MPa														
ETHYL-BENZENE	Chemical formula: C ₈ H ₁₀	Density, ρ _l (kg/m ³)	S	S	951	929	907	885	866	840	797	V	V	V	V
	Molecular weight: 106.17	Specific heat capacity, c _{p,l} (kJ/kg K)	S	S	1.503	1.549	1.612	1.675	1.738	1.880	2.219	V	V	V	V
	Melting point: -95.05 °C	Thermal conductivity, λ _l [(W/m ²)/(K/m)]	S	S	0.151	0.147	0.142	0.137	0.131	0.126	0.110	V	V	V	V
	Boiling point: 136.15 °C	Dynamic viscosity, η _l (10 ⁻⁵ Ns/m ²)	S	S	560	246	135.0	89.5	67.9	48.2	30.8	V	V	V	V
	Critical temperature: 343.95 °C														
	Critical pressure: 3.61 MPa														
VINYL-BENZENE	Chemical formula: C ₈ H ₈	Density, ρ _l (kg/m ³)	S	S	S	S	(942)	922	907	881	838	V	V	V	V
	Molecular weight: 104.15	Specific heat capacity, c _{p,l} (kJ/kg K)	S	S	S	S	1.595	1.654	1.717	1.834	2.052	V	V	V	V
	Melting point: -30.65 °C	Thermal conductivity, λ _l [(W/m ²)/(K/m)]	S	S	S	S	0.148	0.142	0.137	0.131	0.119	V	V	V	V
	Boiling point: 145.15 °C	Dynamic viscosity, η _l (10 ⁻⁵ Ns/m ²)	S	S	S	S	(160)	104.7	74.9	50.2	30.9	V	V	V	V
	Critical temperature: 373.85 °C														
	Critical pressure: 3.99 MPa														
PROPYL-BENZENE	Chemical formula: C ₉ H ₁₂	Density, ρ _l (kg/m ³)	S	S	937	918	898	879	860	833	793	750	V	V	V
	Molecular weight: 120.19	Specific heat capacity, c _{p,l} (kJ/kg K)	S	S	1.540	1.617	1.652	1.715	1.769	1.858	(2.03)	(2.25)	V	V	V
	Melting point: -99.45 °C	Thermal conductivity, λ _l [(W/m ²)/(K/m)]	S	S	0.148	0.143	0.137	0.132	0.128	0.122	0.112	0.102	V	V	V
	Boiling point: 159.25 °C	Dynamic viscosity, η _l (10 ⁻⁵ Ns/m ²)	S	S	—	(320)	191.0	118.3	85.7	58.4	36.0	25.0	V	V	V
	Critical temperature: 365.15 °C														
	Critical pressure: 3.20 MPa														

AROMATICS (Continued)

			Temperature, °C												
			- 150	- 100	- 75	- 50	- 25	0	20	50	100	150	200	250	300
			Temperature, K												
Substance	Data	Property	123.15	173.15	198.15	223.15	248.15	273.15	293.15	323.15	373.15	423.15	473.15	523.15	573.15
ISOPROPYL- BENZENE	Chemical formula: C₉H₁₂	Density, ρ_l(kg/m³)	S	S	(937)	(917)	(897)	878	862	837	(795)	(747)	V	V	V
	Molecular weight: 120.19	Specific heat capacity, c_{p,l} (kJ/kg K)	S	S	(1.53)	(1.58)	(1.64)	(1.71)	1.762	1.853	(2.03)	(2.25)	V	V	V
	Melting point: —96.05 °C	Thermal conductivity, λ_l [(W/m²)/(K/m)]	S	S	0.141	0.136	0.131	0.126	0.122	0.116	0.106	0.097	V	V	V
	Boiling point: 152.45 °C	Dynamic viscosity, η_l (10^{−5} Ns/m²)	S	S	—	(340)	(180)	107.4	78.9	54.0	(33.9)	(23.5)	V	V	V
	Critical temperature: 357.85 °C														
	Critical pressure: 3.21 MPa														
BUTYL- BENZENE	Chemical formula: C₁₀H₁₄	Density, ρ_l(kg/m³)	S	S	934	914	895	877	869	838	798	756	V	V	V
	Molecular weight: 134.22	Specific heat capacity, c_{p,l} (kJ/kg K)	S	S	1.507	1.566	1.629	1.712	1.767	1.896	2.050	(2.21)	V	V	V
	Melting point: —87.95 °C	Thermal conductivity, λ_l [(W/m²)/(K/m)]	S	S	0.147	0.142	0.137	0.132	0.128	0.123	0.113	0.104	V	V	V
	Boiling point: 183.25 °C	Dynamic viscosity, η_l (10^{−5} Ns/m²)	S	S	(2700)	601	250.0	146.6	103.6	68.5	41.1	28.0	V	V	V
	Critical temperature: 387.35 °C														
	Critical pressure: 2.89 MPa														
PENTYL- BENZENE	Chemical formula: C₁₁H₁₆	Density, ρ_l(kg/m³)	S	S	(926)	(908)	(890)	873	859	837	799	(758)	(716)	V	V
	Molecular weight: 148.24	Specific heat capacity, c_{p,l} (kJ/kg K)	S	S	(1.59)	(1.64)	(1.70)	(1.76)	(1.82)	(1.90)	(2.07)	(2.29)	(2.55)	V	V
	Melting point: —78.3 °C	Thermal conductivity, λ_l [(W/m²)/(K/m)]	S	S	0.147	0.142	0.138	0.134	0.130	0.125	0.117	0.108	0.100	V	V
	Boiling point: 231 °C	Dynamic viscosity, η_l (10^{−5} Ns/m²)	S	S	—	(550)	(333)	201.0	133.5	85.3	49.2	32.0	(21)	V	V
	Critical temperature: 452.1 °C														
	Critical pressure: 29.89 MPa														
HEXYL- BENZENE	Chemical formula: C₁₂H₁₈	Density, ρ_l(kg/m³)	S	S	S	(905)	(890)	875	861	844	(811)	(780)	(748)	(716)	V
	Molecular weight: 162.26	Specific heat capacity, c_{p,l} (kJ/kg K)	S	S	S	(1.65)	(1.72)	(1.775)	(1.830)	(1.92)	(2.09)	(2.29)	(2.55)	(2.81)	V
	Melting point: —66.8 °C	Thermal conductivity, λ_l [(W/m²)/(K/m)]	S	S	S	0.142	0.137	0.133	0.130	0.125	0.117	0.108	0.101	0.093	V
	Boiling point: 263 °C	Dynamic viscosity, η_l (10^{−5} Ns/m²)	S	S	S	(800)	(450)	260.1	167.6	103.6	57.4	36.0	(23)	(15)	V
	Critical temperature: 423.6 °C														
	Critical pressure: 25.54 MPa														
o-XYLENE	Chemical formula: C₈H₁₀	Density, ρ_l(kg/m³)	S	S	S	S	(918)	905	881	854	808	V	V	V	V
	Molecular weight: 106.17	Specific heat capacity, c_{p,l} (kJ/kg K)	S	S	S	S	1.633	1.683	1.733	1.839	(2.00)	V	V	V	V
	Melting point: -25.15 °C	Thermal conductivity, λ_l [(W/m²)/(K/m)]	S	S	S	S	(0.146)	0.138	0.134	0.129	0.122	V	V	V	V
	Boiling point: 144.45 °C	Dynamic viscosity, η_l (10^{−5} Ns/m²)	S	S	S	S	(180)	110.0	80.7	55.6	34.4	V	V	V	V
	Critical temperature: 357.25 °C														
	Critical pressure: 3.73 MPa														

m-XYLENE	Chemical formula: C_8H_{10}	Density, ρ_l (kg/m ³)	S	S	S	S	902	881	866	838	795	V	V	V	V
	Molecular weight: 106.17	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	1.587	1.650	1.717	1.806	(1.98)	V	V	V	V
	Melting point: -47.65 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	0.144	0.138	0.132	0.126	0.114	V	V	V	V
	Boiling point: 139.15 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	125	80.2	61.5	44.5	29.0	V	V	V	V
	Critical temperature: 343.85 °C														
p-XYLENE	Critical pressure: 3.543 MPa														
	Chemical formula: C_8H_{10}	Density, ρ_l (kg/m ³)	S	S	S	S	S	S	861	833	790	V	V	V	V
	Molecular weight: 106.17	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	S	S	1.700	1.784	1.959	V	V	V	V
	Melting point: 13.25 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	S	S	0.133	0.126	0.114	V	V	V	V
	Boiling point: 138.35 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	S	64.3	45.6	29.0	V	V	V	V
1,2,3-TRIMETHYL-BENZENE	Critical temperature: 343.05 °C														
	Critical pressure: 3.52 MPa														
	Chemical formula: C_9H_{12}	Density, ρ_l (kg/m ³)	S	S	S	S	(929)	910	894	(871)	(830)	(787)	V	V	V
	Molecular weight: 120.19	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	1.656	1.733	1.787	(1.86)	(2.02)	(2.17)	V	V	V
	Melting point: -25.45 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	0.143	0.137	0.133	0.127	0.117	0.107	V	V	V
1,2,4-TRIMETHYL-BENZENE	Boiling point: 176.05 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	(215)	(135)	(101)	(81)	(52)	(34)	V	V	V
	Critical temperature: 391.35 °C														
	Critical pressure: 3.46 MPa														
	Chemical formula: C_9H_{12}	Density, ρ_l (kg/m ³)	S	S	S	S	(913)	(892)	876	(852)	(811)	(770)	V	V	V
	Molecular weight: 120.19	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	1.641	1.704	1.758	1.837	2.006	(2.19)	V	V	V
1,3,5-TRIMETHYL-BENZENE	Melting point: -46.15 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	0.141	0.136	0.132	0.126	0.115	0.105	V	V	V
	Boiling point: 169.35 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	(215)	(135)	101	81	(52)	(34)	V	V	V
	Critical temperature: 375.95 °C														
	Critical pressure: 3.23 MPa														
	Chemical formula: C_9H_{12}	Density, ρ_l (kg/m ³)	S	S	S	S	(900)	(881)	865	841	(799)	(753)	V	V	V
1,2,3,4-TETRA-METHYL-BENZENE	Molecular weight: 120.19	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	1.578	1.667	1.729	(1.82)	(1.97)	(2.14)	V	V	V
	Melting point: -44.75 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	0.144	0.141	0.136	0.129	0.116	0.108	V	V	V
	Boiling point: 164.75 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	(140)	(98)	73.5	51.4	37.1	(20)	V	V	V
	Critical temperature: 364.15 °C														
	Critical pressure: 3.13 MPa														
1,2,3,4-TETRA-METHYL-BENZENE	Chemical formula: $C_{10}H_{14}$	Density, ρ_l (kg/m ³)	S	S	S	S	S	(921)	905	(882)	(843)	(805)	(767)	V	V
	Molecular weight: 134.22	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	S	1.739	1.790	(1.87)	(2.02)	(2.21)	(2.44)	V	V
	Melting point: -1.8 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	S	(0.143)	(0.139)	(0.133)	(0.127)	(0.114)	(0.105)	V	V
	Boiling point: 204.4 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	(180)	(130)	(83)	(49)	(33)	(23)	V	V
	Critical temperature: 426.9 °C														
1,2,3,4-TETRA-METHYL-BENZENE	Critical pressure: 3.22 MPa														

AROMATICS (Continued)

			Temperature, °C												
			-150	-100	-75	-50	-25	0	20	50	100	150	200	250	300
			Temperature, K												
Substance	Data	Property	123.15	173.15	198.15	223.15	248.15	273.15	293.15	323.15	373.15	423.15	473.15	523.15	573.15
1,2,3,5-TETRA-METHYL-BENZENE	Chemical formula: C₁₀H₁₄	Density, ρ_l(kg/m³)	S	S	S	S	S	—	—	—	—		V	V	V
	Molecular weight: 134.22	Specific heat capacity, c_{p,l} (kJ/kg K)	S	S	S	S	S	1.729	1.779	—	—	—	V	V	V
	Melting point: −24.0 °C	Thermal conductivity, A, [(W/m²)/(K/m)]	S	S	S	S	S	—	—	—	—	—	V	V	V
	Boiling point: 197.9 °C	Dynamic viscosity, η_l (10^{−5} Ns/m²)	S	S	S	S	S	—	—		—		V	V	V
	Critical temperature: 413.6 °C														
	Critical pressure: 3.27 MPa														
1,2,4,5-TETRA-METHYL-BENZENE	Chemical formula: C₁₀H₁₄	Density, ρ_l(kg/m³)	S	S	S	S	S	S	S	S	(819)	(779)	V	V	V
	Molecular weight: 134.22	Specific heat capacity, c_{p,l} (kJ/kg K)	S	S	S	S	S	S	S	S	2.068	2.198	V	V	V
	Melting point: 78.85 °C	Thermal conductivity, λ_l [(W/m²)/(K/m)]	S	S	S	S	S	S	S	S	0.123	0.114	V	V	V
	Boiling point: 196.85 °C	Dynamic viscosity, η_l (10^{−5} Ns/m²)	S	S	S	S	S	S	S	S	(37)	(26)	V	V	V
	Critical temperature: 401.85 °C														
	Critical pressure: 2.94 MPa														
PENTA-METHYL-BENZENE	Chemical formula: C₁₁H₁₆	Density, ρ_l(kg/m³)	S	S	S	S	S	S	S	S	859	(821)	(782)	V	V
	Molecular weight: 148.24	Specific heat capacity, c_{p,l} (kJ/kg K)	S	S	S	S	S	S	S	S	2.031	2.236	(2.55)	V	V
	Melting point: 54.3 °C	Thermal conductivity, A, [(W/m²)/(K/m)]	S	S	S	S	S	S	S	S	0.122	0.113	0.105	V	V
	Boiling point: 231 °C	Dynamic viscosity, η_l (10^{−5} Ns/m²)	S	S	S	S	S	S	S	S	(66)	(40)	(27)	V	V
	Critical temperature: 452.1 °C														
	Critical pressure: 2.99 MPa														
HEXA-METHYL-BENZENE	Chemical formula: C₁₂H₁₈	Density, ρ_l (kg/m³)	S	S	S	S	S	S	S	S	S	S	(800)	(760)	V
	Molecular weight: 162.26	Specific heat capacity, c_{p,l} (kJ/kg K)	S	S	S	S	S	S	S	S	S	S	2.458	(2.64)	V
	Melting point: 165.5 °C	Thermal conductivity, A, [(W/m²)/(K/m)]	S	S	S	S	S	S	S	S	S	S	0.110	0.103	V
	Boiling point: 265 °C	Dynamic viscosity, η_l (10^{−5} Ns/m²)	S	S	S	S	S	S	S	S	S	S	(32)	(23)	V
	Critical temperature: 481 °C														
	Critical pressure: 2.72 MPa														

DIPHENYL	Chemical formula: $C_{12}H_{10}$	Density, ρ_l (kg/m ³)	S	S	S	S	S	S	S	S	970	930	888	848	V
	Molecular weight: 154.21	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	S	S	S	S	1.779	1.968	2.190	2.407	V
	Melting point: 69.25 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	S	S	S	S	0.134	0.127	0.119	0.112	V
	Boiling point: 255.25 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	S	S	S	97.0	55.6	37.2	26.9	V
	Critical temperature: 515.85 °C														
DIPHENYL-METHANE	Chemical formula: $C_{13}H_{12}$	Density, ρ_l (kg/m ³)	S	S	S	S	S	S	S	984	944	904	864	824	V
	Molecular weight: 168.24	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	S	S	S	1.631	1.760	(1.91)	(2.06)	(2.20)	V
	Melting point: 26.85 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	S	S	S	0.132	0.127	0.121	0.115	(0.109)	V
	Boiling point: 264.35 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	S	S	180.1	93.1	56.0	37.5	27.0	V
	Critical temperature: 499.3 °C														
TRIPHENYL-METHANE	Chemical formula: $C_{19}H_{16}$	Density, ρ_l (kg/m ³)	S	S	S	S	S	S	S	S	1014	975	(937)	(899)	(860)
	Molecular weight: 244.32	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	S	S	S	S	1.851	1.913	(1.98)	(2.04)	(2.10)
	Melting point: 93.1 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	S	S	S	S	(0.136)	(0.132)	(0.129)	(0.125)	(0.121)
	Boiling point: 359 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	S	S	S	322.1	(155)	(85)	(53)	(40)
	Critical temperature: (657) °C														
NAPH-THALENE	Chemical formula: $C_{10}H_8$	Density, ρ_l (kg/m ³)	S	S	S	S	S	S	S	S	963	922	(878)	V	V
	Molecular weight: 128.17	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	S	S	S	S	1.805	1.993	2.139	V	V
	Melting point: 80.35 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	S	S	S	S	0.137	0.130	0.123	V	V
	Boiling point: 217.95 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	S	S	S	77.4	52.0	37.5	v	V
	Critical temperature: 475.25 °C														
1-METHYL-NAPH-THALENE	Chemical formula: $C_{11}H_{10}$	Density, ρ_l (kg/m ³)	S	S	S	S	(1053)	1035	1020	998	962	(924)	(884)	V	V
	Molecular weight: 142.20	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	1.424	1.509	1.564	1.661	(1.82)	(1.95)	(2.11)	v	V
	Melting point: -30.45 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	(0.136)	(0.133)	(0.130)	(0.127)	(0.120)	(0.114)	(0.107)	V	V
	Boiling point: 244.65 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	(1400)	(571)	333	167	(85)	(50)	(32)	V	V
	Critical temperature: 498.85 °C														
2-METHYL-NAPH-THALENE	Chemical formula: $C_{11}H_{10}$	Density, ρ_l (kg/m ³)	S	S	S	S	S	S	S	984	947	908	(868)	v	V
	Molecular weight: 142.20	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	S	S	S	1.632	1.805	(1.98)	(2.17)	V	V
	Melting point: 34.55 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	S	S	S	0.127	0.120	(0.114)	(0.107)	v	V
	Boiling point: 241.05 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	S	S	136.1	(72)	(43)	(30)	V	V
	Critical temperature: 487.85 °C														
	Chemical formula: $C_{11}H_{10}$	Density, ρ_l (kg/m ³)	S	S	S	S	S	S	S	S	970	930	888	848	V
	Molecular weight: 154.21	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	S	S	S	S	1.779	1.968	2.190	2.407	V
	Melting point: 69.25 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	S	S	S	S	0.134	0.127	0.119	0.112	V
	Boiling point: 255.25 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	S	S	S	97.0	55.6	37.2	26.9	V
	Critical temperature: 515.85 °C														

AROMATICS (Continued)

			Temperature, °C												
			- 150	- 100	- 75	- 50	- 25	0	20	50	100	150	200	250	300
			Temperature, K												
Substance	Data	Property	123.15	173.15	198.15	223.15	248.15	273.15	293.15	323.15	373.15	423.15	473.15	523.15	573.15
1-ETHYL-NAPH-THALENE	Chemical formula: C ₁₂ H ₁₂	Density, ρ _l (kg/m ³)	S	S	S	S	(1.039)	1.022	1008	987	950	(913)	(874)	(832)	V
	Molecular weight: 156.22	Specific heat capacity, c _{p,l} (kJ/kg K)	S	S	S	S	(1.52)	(1.58)	(1.63)	(1.71)	(1.85)	(1.98)	(2.10)	(2.22)	V
	Melting point: −27.0 °C	Thermal conductivity, λ _l [(W/m ²)/(K/m)]	S	S	S	S	(0.134)	(0.131)	(0.129)	(0.126)	(0.121)	(0.115)	(0.110)	(0.104)	V
	Boiling point: 258.3 °C	Dynamic viscosity, η _l (10 ^{−5} Ns/m ²)	S	S	S	S	(1400)	(571)	(333)	(167)	(85)	(50)	(32)	(19)	V
	Critical temperature: 502.4 °C														
2-ETHYL-NAPH-THALENE	Critical pressure: 3.99 MPa														
	Chemical formula: C ₁₂ H ₁₂	Density, ρ _l (kg/m ³)	S	S	S	S	S	1008	992	(971)	(935)	(896)	(855)	(810)	V
	Molecular weight: 156.22	Specific heat capacity, c _{p,l} (kJ/kg K)	S	S	S	S	S	(1.58)	(1.63)	(1.71)	(1.85)	(1.98)	(2.10)	(2.22)	V
	Melting point: −7.4 °C	Thermal conductivity, λ _l [(W/m ²)/(K/m)]	S	S	S	S	S	(0.131)	(0.129)	(0.126)	(0.121)	(0.115)	(0.110)	(0.104)	V
	Boiling point: 257.9 °C	Dynamic viscosity, η _l (10 ^{−5} Ns/m ²)	S	S	S	S	S	(350)	(240)	(136)	(72)	(43)	(30)	(17)	V
	Critical temperature: 498.6 °C														
	Critical pressure: 3.17 MPa														

ALCOHOLS

Substance	Data	Property	Temperature, °C												
			-150	-100	-75	-50	-25	0	20	50	100	150	200	250	300
			Temperature, K												
			123.15	173.15	198.15	223.15	248.15	273.15	293.15	323.15	373.15	423.15	473.15	523.15	573.15
METHANOL	Chemical formula: CH ₄ O	Density, ρ_l (kg/m ³)	S	S	905	900	858	810	792	765	V	V	V	V	V
	Molecular weight: 32.04	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	2.194	1.240	2.294	2.386	2.495	2.680	V	V	V	V	V
	Melting point: -98.0 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	0.235	0.225	0.215	0.208	0.202	0.193	V	V	V	V	V
	Boiling point: 64.7 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	479	230.6	128.0	81.7	58.4	39.6	V	V	V	V	V
	Critical temperature: 240 °C														
ETHANOL	Critical pressure: 7.95 MPa														
	Chemical formula: C ₂ H ₆ O	Density, ρ_l (kg/m ³)	S	892	870	850	825	806	789	763	V	V	V	V	V
	Molecular weight: 46.07	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	1.901	1.947	2.014	2.093	2.232	2.395	2.801	V	V	V	V	V
	Melting point: -114.5 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	0.197	0.193	0.188	0.183	0.177	0.173	0.165	V	V	V	V	V
	Boiling point: 78.3 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	4 701	1 526	640	324.1	1768.6	120.1	70.1	V	V	V	V	V
1-PROPANOL	Critical temperature: 243.10 °C														
	Critical pressure: 6.39 MPa														
	Chemical formula: C ₃ H ₈ O	Density, ρ_l (kg/m ³)	S	(872)	(862)	(849)	(835)	818	804	779	V	V	V	V	V
	Molecular weight: 60.10	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	1.805	1.855	1.955	2.077	2.219	2.345	2.571	V	V	V	V	V
	Melting point: -127 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	0.172	0.170	0.167	0.164	0.160	0.157	0.153	V	V	V	V	V
1-BUTANOL	Boiling point: 97.8 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	(61000)	7 562	2 020	820	413.7	223.1	112.6	V	V	V	V	V
	Critical temperature: 263.7 °C														
	Critical pressure: 5.05 MPa														
	Chemical formula: C ₄ H ₁₀ O	Density, ρ_l (kg/m ³)	S	S	(854)	(845)	835	825	810	791	753	V	V	V	V
	Molecular weight: 74.12	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	1.859	1.947	2.056	2.202	2.345	2.621	(2.84)	V	V	V	V
1-PENTANOL	Melting point: -89.95 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	0.170	0.165	0.162	0.158	0.155	0.149	0.138	V	V	V	V
	Boiling point: 117.5 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	(9400)	3 471	1 250	530	295.1	142.0	53.1	V	V	V	V
	Critical temperature: 288.0 °C														
	Critical pressure: 4.42 MPa														
	Chemical formula: C ₅ H ₁₂ O	Density, ρ_l (kg/m ³)	S	S	(895)	(874)	(853)	829	814	(786)	(734)	V	V	V	V
1-PENTANOL	Molecular weight: 88.15	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	1.863	1.930	2.026	2.161	2.315	2.625	3.287	V	V	V	V
	Melting point: -78.15 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	0.171	0.167	0.163	0.159	0.156	0.151	0.142	V	V	V	V
	Boiling point: 137.85 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	(20000)	(8000)	(2900)	1 110	510	200.1	60.3	V	V	V	V
	Critical temperature: 312.85 °C														
	Critical pressure: 3.85 MPa														

ALCOHOLS (Continued)															
			-150	-100	-75	-50	-25	0	Temperature, °C		100	150	200	250	300
			Temperature, K												
Substance	Data	Property	123.15	173.15	198.15	223.15	248.15	273.15	293.15	323.15	373.15	423.15	473.15	523.15	573.15
1-HEXANOL	Chemical formula: C ₆ H ₁₄ O	Density, ρ _l (kg/m ³)	S	S	S	S	852	833	820	(797)	(758)	(715)	v	V	V
	Molecular weight: 102.18	Specific heat capacity, c _{p,l} (kJ/kg K)	S	S	S	S	1.813	1.976	2.173	(2.57)	(3.10)	(3.46)	V	V	V
	Melting point: -43.95 °C	Thermal conductivity, A, [(W/m ²)/(K/m)]	S	S	S	S	0.150	0.146	0.143	0.140	0.131	0.128	V	V	V
	Boiling point: 157.05 °C	Dynamic viscosity, η _l (10 ⁻⁵ Ns/m ²)	S	S	S	S	(3200)	1 079	542.7	216.0	79.4	36.7	V	V	V
	Critical temperature: 336.85 °C														
1-HEPTANOL	Chemical formula: C ₇ H ₁₆ O	Density, ρ _l (kg/m ³)	S	S	S	S	(863)	839	822	795	756	722	V	V	V
	Molecular weight: 116.20	Specific heat capacity, c _{p,l} (kJ/kg K)	S	S	S	S	2.031	2.220	2.358	(2.91)	(3.46)	(3.54)	V	V	V
	Melting point: -32.8 °C	Thermal conductivity, A, [(W/m ²)/(K/m)]	S	S	S	S	0.145	0.140	0.137	0.133	(0.126)	(0.120)	V	V	V
	Boiling point: 175.9 °C	Dynamic viscosity, η _l (10 ⁻⁵ Ns/m ²)	S	S	S	S	(4800)	(1490)	701.1	268.1	80.0	41.5	v	V	V
	Critical temperature: 368.7 °C														
I-OCTANOL	Chemical formula: C ₈ H ₁₈ O	Density, ρ _l (kg/m ³)	S	S	S	S	S	842	829	809	773	(734)	v	V	V
	Molecular weight: 130.23	Specific heat capacity, c _{p,l} (kJ/kg K)	S	S	S	S	S	2.156	2.219	(2.55)	(2.92)	(3.25)	V	V	V
	Melting point: -15.45 °C	Thermal conductivity, λ _l [(W/m ²)/(K/m)]	S	S	S	S	S	0.140	0.137	0.133	(0.126)	(0.119)	V	V	V
	Boiling point: 179.75 °C	Dynamic viscosity, η _l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	1 980	893.3	321.7	106	46	V	V	V
	Critical temperature: 363.85 °C														
ISOPROPANOL	Chemical formula: C ₃ H ₈ O	Density, ρ _l (kg/m ³)	S	S	(844)	832	818	801	785	764	V	V	V	V	V
	Molecular weight: 60.10	Specific heat capacity, c _{p,l} (kJ/kg K)	S	S	1.830	1.930	2.073	2.265	2.496	2.956	V	V	V	V	V
	Melting point: -79 °C	Thermal conductivity, A, [(W/m ²)/(K/m)]	S	S	0.158	0.153	0.149	0.144	0.141	0.135	V	V	V	V	V
	Boiling point: 82.5 °C	Dynamic viscosity, η _l (10 ⁻⁵ Ns/m ²)	S	S	(11000)	3 761	1 250	460.1	243.2	106.3	v	V	V	V	V
	Critical temperature: 235.6 °C														
	Critical pressure: 5.37 MPa														

ISOBUTANOL	Chemical formula: $C_4H_{10}O$	Density, ρ_l (kg/m ³)	S	(887)	(870)	(853)	(835)	817	806	794	732	V	V	V	V
	Molecular weight: 74.12	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	1.736	1.786	1.875	2.052	2.156	2.311	2.684	(3.40)	v	V	V	V
	Melting point: -107.95 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	0.157	0.152	0.147	0.142	0.137	0.133	0.127	0.119	v	V	V	V
	Boiling point: 107.85 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S		—	(13000)	2300.6	800	390.1	162.0	52.0	V	V	V	V
ISOPENTANOL	Critical temperature: 274.55 °C														
	Critical pressure: 4.30 MPa														
	Chemical formula: $C_5H_{12}O$	Density, ρ_l (kg/m ³)	S	(909)	(891)	(870)	(840)	824	810	(782)	(730)	V	V	V	V
	Molecular weight: 88.15	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	(1.76)	(1.81)	(1.88)	(2.00)	(2.16)	2.345	(2.66)	(3.17)	V	V	V	V
t-BUTYL ALCOHOL	Melting point: -117.2 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	0.157	0.152	1.147	0.141	0.137	0.133	0.128	0.120	V	V	V	V
	Boiling point: 130.6 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	—	(12000)	(5000)	(2100)	860.2	430.1	185.1	62.0	V	V	V	V
	Critical temperature: 306.65 °C														
	Critical pressure: 3.85 MPa														
ETHYLENE GLYCOL	Chemical formula: C_2H_6O	Density, ρ_l (kg/m ³)	S	S	S	S	S	S	S	750	v	V	V	V	V
	Molecular weight: 62.07	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	S	S	S	3.18	V	V	V	V	V
	Melting point: -12.95 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	S	S	S	0.106	v	V	V	V	V
	Boiling point: 197.25 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	S	S	144	v	V	V	V	V
1,3-PROPYLENE GLYCOL	Critical temperature: 371.85 °C														
	Critical pressure: 7.7 MPa														
	Chemical formula: $C_3H_8O_2$	Density, ρ_l (kg/m ³)	S	S	S	S	(1083)	(1066)	1 053	1033	1003	964	(920)	V	V
	Molecular weight: 76.10	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	2.240	2.361	2.469	2.647	2.950	3.242	(3.51)	V	V
GLYCEROL	Melting point: -26.75 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	0.193	0.198	0.201	0.203	0.203	0.195	0.179	V	V
	Boiling point: 214.45 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	(97500)	17160	5260	1 540	360	130	(64)	V	V
	Critical temperature: 384.85 °C														
	Critical pressure: 5.98 MPa														
GLYCEROL	Chemical formula: $C_3H_8O_3$	Density, ρ_l (kg/m ³)	S	S	S	S	S	S	1260	1 242	1 154	1090	(1007)	V	
	Molecular weight: 92.09	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	S	S	2.366	2.512	2.805	3.06	3.34	(3.74)	V
	Melting point: 17.85 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	S	S	0.286	0.290	0.297	0.300	0.295	0.282	V
	Boiling point: 290 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	S	149900	(18000)	1300	170	22.0	(3.0)	V
	Critical temperature: 452.85 °C														
	Critical pressure: 6.69 MPa														

ALCOHOLS (Continued)

Substance	Data	Property	Temperature, °C												
			-150	-100	-75	-50	-25	0	20	50	100	150	200	250	300
			Temperature, K												
			123.15	173.15	198.15	223.15	248.15	273.15	293.15	323.15	373.15	423.15	473.15	523.15	573.15
CYCLO- HEXANOL	Chemical formula: $C_6H_{12}O$	Density, ρ_l (kg/m ³)	S	S	S	S	S	S	S	925	874	821	V	V	V
	Molecular weight: 100.16	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	S	S	S	(2.03)	(2.32)	(2.56)	V	V	V
	Melting point: 24.85 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	S	S	S	0.132	0.124	0.117	V	V	V
	Boiling point: 161.15 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	S	S	1181	185.1	68.9	V	V	V
	Critical temperature: 351.15 °C														
BENZYL ALCOHOL	Critical pressure: 3.75 MPa														
	Chemical formula: C_7H_8O	Density, ρ_l (kg/m ³)	S	S	S	S	S	1061	1045	1022	983	940	893	V	V
	Molecular weight: 108.14	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	S	1.860	1.972	2.135	(2.37)	(2.53)	(2.60)	V	V
	Melting point: -15.35 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	S	(0.161)	0.160	(0.158)	0.156	0.152	(0.151)	V	V
	Boiling point: 205.45 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	(1200)	558.4	257.4	102	56	35	V	V
	Critical temperature: 403.85 °C														
	Critical pressure: 4.66 MPa														

PHENOLS

			Temperature, °C												
			-150	-75		-25		0	20	50	100	150	200	250	300
Substance	Data	Property	123.15	173.15	198.15	223.15	248.15	273.15	293.15	323.15	373.15	423.15		523.15	573.15
PHENOL	C₆H₆O 40.75 °C Boiling point: 18 1.8 °C 420.05 °C Critical pressure: 6.13 MPa	ρ_l (kg/m ³)	S	S	S	S	S	S	S	1 050	973	931	v	V	V
		Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	S	S	S	2.244	2.382	(2.42)	V	V	V
		Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	S	S	S	0.156	0.135	(0.130)	v	V	V
		Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	S	S	342.1	105.0	67.0	V	V	V
o-CRESOL	C₇H₈O Melting point: 30.95 °C Boiling point: 191.05 °C Critical temperature: 424.45 °C Critical pressure: 5.01 MPa	ρ_l (kg/m ³)	S	S	S	S	S	S	1 020	979	934	V	V	V	
		Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	S	S	S	2.20	2.28	2.35	V	V	V
		Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	S	S	S	0.153	0.143	0.138	V	V	V
		Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	S	S	300	100.0	50.4	v	V	V
m-CRESOL	Chemical formula: C₇H₈O Molecular weight: 108.14 Melting point: 12.25 °C Boiling point: 202.25 °C Critical temperature: 432.65 °C Critical pressure: 4.56 MPa	Density, ρ_l (kg/m ³)	S	S	S	S	S	S	1 034	1009	973	(930)	(882)	V	V
		Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	S	S	2.010	2.158	2.303	(2.40)	(2.51)	V	V
		Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	S	S	0.150	0.148	0.143	0.135	(0.130)	v	V
		Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	S	1 691	420.1	120.0	57.4	34.7	v	V
p-CRESOL	Chemical formula: C₇H₈O Molecular weight: 108.14 Melting point: 34.75 °C Boiling point: 201.95 °C Critical temperature: 426 °C Critical pressure: 5.15 MPa	Density, ρ_l (kg/m ³)	S	S	S	S	S	S	S	1011	973	931	(883)	V	V
		Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	S	S	S	2.162	2.310	(2.43)	(2.50)	V	V
		Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	S	S	S	0.141	0.135	(0.130)	(0.126)	V	V
		Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	S	S	465.1	130.0	61.2	37.1	v	V

ESTERS

Substance	Data	Property	Temperature, °C												
			-150	-100	-75	-50	-25	0	20	50	100	150	200	250	300
			Temperature, K												
			123.15	173.15	198.15	223.15	248.15	273.15	293.15	323.15	373.15	423.15	473.15	523.15	573.15
METHYL FORMATE	Chemical formula: $C_2H_4O_2$	Density, ρ_l (kg/m ³)	S	S	(1.102)	(1.069)	(1.036)	1003	975	V	V	V	V	V	V
	Molecular weight: 60.05	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	(1.80)	(1.84)	(1.89)	(1.95)	2.026	V	V	V	V	V	V
	Melting point: -98.95 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	(0.228)	0.217	0.206	0.195	0.186	V	V	V	V	V	V
	Boiling point: 3 1.75 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	(115)	(83)	(59)	43.1	34.5	V	V	V	V	V	V
	Critical temperature: 214.05 °C														
ETHYL FORMATE	Chemical formula: $C_3H_6O_2$	Density, ρ_l (kg/m ³)	S	S	(1020)	(998)	(976)	948	923	883	V	V	V	V	V
	Molecular weight: 74.08	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	(1.72)	(1.74)	(1.76)	(1.80)	1.989	2.177	V	V	V	V	V
	Melting point: -79.35 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	0.195	0.186	0.177	0.168	0.161	0.152	V	V	V	V	V
	Boiling point: 54.25 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	(115)	(86)	(65)	50.5	40.8	30.6	V	V	V	V	V
	Critical temperature: 235.25 °C														
PROPYL FORMATE	Chemical formula: $C_4H_8O_2$	Density, ρ_l (kg/m ³)	S	S	(1013)	(985)	(957)	929	906	871	V	V	V	V	V
	Molecular weight: 88.11	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	(1.91)	(1.92)	(1.93)	(1.96)	(1.98)	(2.05)	V	V	V	V	V
	Melting point: -92.85 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	0.175	0.167	0.160	0.153	0.147	0.139	V	V	V	V	V
	Boiling point: 80.55 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	—	(90)	(90)	66.7	51.5	37.0	V	V	V	V	V
	Critical temperature: 264.85 °C														
METHYL ACETATE	Chemical formula: $C_3H_6O_2$	Density, ρ_l (kg/m ³)	S	S	(1045)	1018	989	959	934	894	V	V	V	V	V
	Molecular weight: 74.08	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	(1.757)	(1.822)	(1.887)	1.953	2.119	(2.18)	V	V	V	V	V
	Melting point: -98.7 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	0.190	0.182	0.173	0.164	0.157	0.148	V	V	V	V	V
	Boiling point: 57.15 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	(118)	(87)	(64)	47.7	38.9	28.6	V	V	V	V	V
	Critical temperature: 233.65 °C														
ETHYL ACETATE	Chemical formula: $C_4H_8O_2$	Density, ρ_l (kg/m ³)	S	S	(999)	(976)	(951)	924	901	864	V	V	V	V	V
	Molecular weight: 88.11	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	1.821	1.821	1.838	1.880	1.922	1.968	V	V	V	V	V
	Melting point: -83.6 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	0.171	0.164	0.156	0.150	0.144	0.135	V	V	V	V	V
	Boiling point: 77.1 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	(150)	(109)	(80)	58.1	45.2	34.5	V	V	V	V	V
	Critical temperature: 250.1 °C														
ETHYL ACETATE	Chemical formula: $C_4H_8O_2$	Density, ρ_l (kg/m ³)	S	S	(999)	(976)	(951)	924	901	864	V	V	V	V	V
	Molecular weight: 88.11	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	1.821	1.821	1.838	1.880	1.922	1.968	V	V	V	V	V
	Melting point: -83.6 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	0.171	0.164	0.156	0.150	0.144	0.135	V	V	V	V	V
	Boiling point: 77.1 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	(150)	(109)	(80)	58.1	45.2	34.5	V	V	V	V	V
	Critical temperature: 250.1 °C														
ETHYL ACETATE	Chemical formula: $C_4H_8O_2$	Density, ρ_l (kg/m ³)	S	S	(999)	(976)	(951)	924	901	864	V	V	V	V	V
	Molecular weight: 88.11	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	1.821	1.821	1.838	1.880	1.922	1.968	V	V	V	V	V
	Melting point: -83.6 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	0.171	0.164	0.156	0.150	0.144	0.135	V	V	V	V	V
	Boiling point: 77.1 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	(150)	(109)	(80)	58.1	45.2	34.5	V	V	V	V	V
	Critical temperature: 250.1 °C														

PROPYL ACETATE	Chemical formula: $C_3H_6O_2$	S	S	(979)	(956)	(933)	910	888	855	796	V	V	V
	Molecular weight: 102.13	S	S	1.78	1.79	1.82	1.87	1.91	1.99	2.13	V	V	V
	Melting point: -95.15°C	S	S	(0.162)	0.156	0.150	0.143	0.138	0.132	0.119	V	V	V
	Boiling point: 101.65°C	S	S	(285)	(182)	(118)	77.1	53.7	39.0	26.1	V	V	V
	Critical temperature: 276.25°C	S	S	(1026)	(997)	(968)	939	915	879	V	V	V	V
METHYL PROPIONATE	Chemical formula: $C_4H_8O_2$	S	S	(1.79)	(1.82)	(1.87)	(1.92)	(1.96)	(2.04)	V	V	V	V
	Molecular weight: 88.11	S	S	0.174	0.167	0.159	0.152	0.146	0.138	V	V	V	V
	Melting point: -87.45°C	S	S	—	—	(110)	77.3	58.6	41.6	V	V	V	V
	Boiling point: 79.85°C	S	S	(960)	(935)	(912)	880	856	V	V	V	V	V
	Critical temperature: 257.45°C	S	S	(1.78)	(1.83)	(1.88)	1.948	2.034	V	V	V	V	V
ETHYL PROPIONATE	Chemical formula: $C_5H_{10}O_2$	S	S	(977)	(952)	(927)	902	882	(848)	(787)	V	V	V
	Molecular weight: 102.13	S	S	(1.84)	(1.88)	(1.92)	(1.96)	(2.00)	2.072	(2.40)	V	V	V
	Melting point: -73.85°C	S	S	0.158	0.152	0.147	0.141	0.136	0.132	0.119	V	V	V
	Boiling point: 122.55°C	S	S	—	—	(99)	69.0	53.1	37.5	(22)	V	V	V
	Critical temperature: 304.85°C	S	S	(1004)	(976)	(948)	920	897	865	807	V	V	V
PROPYL PROPIONATE	Chemical formula: $C_6H_{12}O_2$	S	S	(1.92)	(1.95)	(1.98)	(2.00)	(2.02)	2.114	(2.24)	V	V	V
	Molecular weight: 116.16	S	S	(0.164)	0.158	0.152	0.145	0.140	0.133	0.121	V	V	V
	Melting point: -75.85°C	S	S	—	—	(120)	76.3	57.9	41.3	26.5	V	V	V
	Boiling point: 122.55°C	S	S	(981)	(954)	(927)	900	879	847	(794)	V	V	V
	Critical temperature: 304.85°C	S	S	(1.76)	(1.80)	(1.84)	(1.86)	1.888	1.96	2.11	V	V	V
METHYL BUTANOATE	Chemical formula: $C_5H_{10}O_2$	S	S	0.159	0.153	0.147	0.141	0.137	0.130	0.119	V	V	V
	Molecular weight: 102.13	S	S	—	—	(120)	76.0	57.7	40.6	25.5	V	V	V
	Melting point: -84.75°C	S	S	(981)	(954)	(927)	900	879	847	(794)	V	V	V
	Boiling point: 102.65°C	S	S	(1.76)	(1.80)	(1.84)	(1.86)	1.888	1.96	2.11	V	V	V
	Critical temperature: 281.25°C	S	S	0.159	0.153	0.147	0.141	0.137	0.130	0.119	V	V	V
ETHYL BUTANOATE	Chemical formula: $C_6H_{12}O_2$	S	S	—	—	(120)	76.0	57.7	40.6	25.5	V	V	V
	Molecular weight: 116.16	S	S	(981)	(954)	(927)	900	879	847	(794)	V	V	V
	Melting point: -93.15°C	S	S	(1.76)	(1.80)	(1.84)	(1.86)	1.888	1.96	2.11	V	V	V
	Boiling point: 120.85°C	S	S	0.159	0.153	0.147	0.141	0.137	0.130	0.119	V	V	V
	Critical temperature: 292.85°C	S	S	—	—	(120)	76.0	57.7	40.6	25.5	V	V	V

ESTERS (Continued)

			Temperature, °C												
			-150	-100	-15	-50	-25	0	20	50	100	150	200	250	300
			Temperature, K												
Data	Property		123.15	173.15	198.15	223.15	248.15	273.15	293.15	323.15	373.15	423.15	473.15	523.15	573.15
METHYL BENZOATE	Chemical formula: C ₈ H ₈ O ₂	Density, ρ _l (kg/m ³)	S	S	S	S	S	1108	1088	(1059)	(1011)	(963)	V	V	V
	Molecular weight: 136.15	Specific heat capacity, c _{p,l} (kJ/kg K)	S	S	S	S	S	1.520	(1.58)	(1.66)	(1.80)	(1.95)	V	V	V
	Melting point: −12.35 °C	Thermal conductivity, λ _l [(W/m ²)/(K/m)]	S	S	S	S	S	0.151	0.147	0.141	0.131	0.121	V	V	V
	Boiling point: 199.05 °C	Dynamic viscosity, η _l (10 ^{−5} Ns/m ²)	S	S	S	S	S	(86)	66.7	46.4	(31)	—	V	V	V
	Critical temperature: 418.85 °C														
ETHYL BENZOATE	Critical pressure: 3.65 MPa														
	Chemical formula: C ₉ H ₁₀ O ₂	Density, ρ _l (kg/m ³)	S	S	S	S	(1083)	1064	1046	1 020	(974)	(930)	(884)	V	V
	Molecular weight: 150.18	Specific heat capacity, c _{p,l} (kJ/kg K)	S	S	S	S	(1.46)	(1.54)	(1.60)	(1.68)	(1.84)	(1.99)	(2.14)	V	V
	Melting point: -34.85 °C	Thermal conductivity, λ _l [(W/m ²)/(K/m)]	S	S	S	S	0.151	0.146	0.142	0.136	0.127	0.118	0.109	v	V
	Boiling point: 212.75 °C	Dynamic viscosity, η _l (10 ^{−5} Ns/m ²)	S	S	S	S	—		206.7	110	67	49.1	(42)	V	V
METHYL SALICYLATE	Critical temperature: 423.85 °C														
	Critical pressure: 3.24 MPa														
	Chemical formula: C ₈ H ₈ O ₃	Density, ρ _l (kg/m ³)	S	S	S	S	S	(1162)	1 180	1 152	1 105	1 055	1004	v	V
	Molecular weight: 152.14	Specific heat capacity, c _{p,l} (kJ/kg K)	S	S	S	S	S	(1.54)	(1.58)	(1.63)	(1.76)	(1.83)	(1.92)	V	V
	Melting point: −8.6 °C	Thermal conductivity, λ _l [(W/m ²)/(K/m)]	S	S	S	S	S	(0.152)	(0.149)	(0.143)	(0.133)	(0.124)	(0.115)	v	V
METHYL SALICYLATE	Boiling point: 223.3 °C	Dynamic viscosity, η _l (10 ^{−5} Ns/m ²)	S	S	S	S	S	348.0	222.0	110.0	82.0	50.2	34.7	v	V
	Critical temperature: 436° C														
METHYL SALICYLATE	Critical pressure: 4.09 MPa														

ALDEHYDES

Substance	Data	Property	Temperature, °C												
			-150	-100	-75	-50	-25	0	20	50	100	150	200	250	300
			Temperature, K												
			123.15	173.15	198.15	223.15	248.15	273.15	293.15	323.15	373.15	423.15	473.15	523.15	573.15
FORMAL- DEHYDE	Chemical formula: CH_2O	Density, ρ_l (kg/m ³)	S	(932)	(895)	(858)	821	V	V	V	V	V	V	V	V
	Molecular weight: 30.03	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	(2.30)	(2.39)	(2.47)	(2.62)	V	V	V	V	V	V	V	V
	Melting point: -117.15 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	0.315	0.293	0.271	0.250	V	V	V	V	V	V	V	V
	Boiling point: -19.15 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S			(24)	(19)	v	v	V	V	V	V	V	V
	Critical temperature: 134.85 °C														
ACETAL- DEHYDE	Chemical formula: $\text{C}_2\text{H}_4\text{O}$	Density, ρ_l (kg/m ³)	S	(920)	(892)	(863)	(834)	804	783	V	V	V	V	V	V
	Molecular weight: 44.05	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	(1.97)	(2.00)	(2.05)	(2.13)	2.20	2.28	V	V	V	V	V	V
	Melting point: -124° C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	0.238	0.224	0.211	0.197	0.184	0.180	V	V	V	V	V	V
	Boiling point: 20.45 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	—	—	(46)	(35)	26.8	22.2	V	V	V	V	V	V
	Critical temperature: 187.85 °C														
PARAL- DEHYDE	Chemical formula: $\text{C}_6\text{H}_{12}\text{O}_3$	Density, ρ_l (kg/m ³)	S	S	S	S	S	S	994	956	899	V	V	V	V
	Molecular weight: 132.15	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	S	S	1.933	(2.03)	(2.22)	V	V	V	V
	Melting point: 12.6 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	S	S	0.145	0.142	0.135	V	V	V	V
	Boiling point: 124.0 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	S	117.9	69.0	37.0	V	V	V	V
	Critical temperature: 290 °C														
FURFURAL	Chemical formula: $\text{C}_5\text{H}_4\text{O}_2$	Density, ρ_l (kg/m ³)	S	S	S	S	(1201)	1 181	1 160	1 128	1 077	(1 020)	v	V	V
	Molecular weight: 96.08	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	(1.47)	1.541	1.636	1.750	(1.87)	(2.00)	v	V	V
	Melting point: -36.5 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	(0.184)	(0.178)	0.172	0.167	(0.155)	(0.142)	V	V	V
	Boiling point: 160.55 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	(410)	247.6	163.1	(120)	(64)	(38)	V	V	V
	Critical temperature: 397° C														
BENZAL- DEHYDE	Chemical formula: $\text{C}_7\text{H}_6\text{O}$	Density, ρ_l (kg/m ³)	S	S	S	(1106)	(1084)	1 062	1046	1 017	971	924	V	V	V
	Molecular weight: 106.12	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	1.474	1.515	1.565	1.610	1.632	1.804	1.926	V	V	V
	Melting point: -57.15 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	0.167	0.162	0.157	0.154	0.148	0.139	0.129	V	V	V
	Boiling point: 178.85 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	—	(330)	230.1	160.1	(95)	—	V	V	V	V
	Critical temperature: 421.85 °C														
BENZAL- DEHYDE	Critical pressure: 4.66 MPa														

ALDEHYDES (Continued)

Substance	Data	Property	Temperature, °C												
			-150	-100	-75	-50	-25	0	20	50	100	150	200	250	300
			Temperature, K												
SALICYAL- DEHYDE	Chemical formula: $C_7H_6O_7$	Density, ρ_l (kg/m ³)	S	S	S	S	S	S	1 150	1 132	1084	1 034	v	V	V
	Molecular weight: 122.12	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	S	S	1.608	(1.71)	(1.89)	(2.07)	V	V	V
	Melting point: 1.6 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	S	S	(0.154)	(0.148)	(0.139)	(0.129)	V	V	V
	Boiling point: 196.5 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	S	320.1	150.0	80.0	49.1	v	V	V
	Critical temperature: (423) °C														
Critical pressure: (5.4) MPa															

KETONES

Substance	Data	Property	Temperature, °C												
			-150	-100	-75	-50	-25	0	20	50	100	150	200	250	300
			Temperature, K												
KETENE	Chemical formula: C_2H_2O	Density, ρ_l (kg/m ³)	S	(1080)	(1030)	(979)	v	V	V	V	V	V	V	V	V
	Molecular weight: 42.04	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	(1.79)	(1.92)	(2.02)	V	V	V	V	V	V	V	V	V
	Melting point: -135.15 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	(0.267)	(0.250)	(0.233)	V	V	V	V	V	V	V	V	V
	Boiling point: -41.15 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	—	—	(110)	v	V	V	V	V	V	V	V	V
	Critical temperature: 106.85 °C														
Critical pressure: 6.48 MPa															
ACETONE	Chemical formula: C_3H_6O	Density, ρ_l (kg/m ³)	S	S	893	868	840	812	791	756	V	V	V	V	V
	Molecular weight: 58.08	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	2.010	2.039	2.072	2.102	2.156	2.252	V	V	V	V	V
	Melting point: -93.2 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	0.179	0.175	0.170	0.165	0.160	0.154	V	V	V	V	V
	Boiling point: 56.1 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	134.1	82.0	56.0	39.8	32.5	24.9	V	V	V	V	V
	Critical temperature: 235 °C														
Critical pressure: 4.761 MPa															

METHYL-ETHYL KETONE	Chemical formula: C₄H₈O	Density, ρ_l (kg/m ³)	S	S	(893)	(870)	(847)	826	803	(773)	V	V	V	V	V
	Molecular weight: 72.11	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	2.071	2.091	2.120	2.155	2.219	2.311	V	V	V	V	V
	Melting point: -86.65 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	0.169	0.163	0.156	0.150	0.145	0.137	V	V	V	V	V
	Boiling point: 79.65 °C Critical temperature: 262.45 °C Critical pressure: 4.15 MPa	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	(125)	(94)	(70)	54.0	42.3	31.0	V	V	V	V	V
DIETHYL KETONE	Chemical formula: C₅H₁₀O	Density, ρ_l (kg/m ³)	S	S	S	S	(858)	834	914	787	(740)	v	V	V	V
	Molecular weight: 86.13	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	2.139	2.171	2.214	2.268	2.418	V	V	V	V
	Melting point: -38.95 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	0.153	0.147	0.142	0.135	(0.123)	V	V	V	V
	Boiling point: 101.95 °C Critical temperature: 287.85 °C Critical pressure: 3.74 MPa	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	(77)	59.4	47.0	34.4	22.5	V	V	V	V
DIPROPYL KETONE	Chemical formula: C₇H₁₄O	Density, ρ_l (kg/m ³)	S	S	S	S	(853)	832	817	790	748	V	V	V	V
	Molecular weight: 114.18	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	(2.10)	(2.14)	(2.18)	2.198	2.407	V	V	V	V
	Melting point: -34.0 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	0.148	0.144	0.140	0.133	(0.122)	v	V	V	V
	Boiling point: 143.5 °C Critical temperature: 331 °C Critical pressure: 3.0 MPa	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	—	(100)	75.1	(52)	(33)	V	V	V	V
ACETO-PHENONE	Chemical formula: C₈H₈O	Density, ρ_l (kg/m ³)	S	S	S	S	S	S	1 028	1002	958	914	(865)	V	V
	Molecular weight: 120.14	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	S	S	1.88	1.93	1.968	(2.03)	(2.09)	v	V
	Melting point: -19.6 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	S	S	0.142	0.140	0.132	(0.123)	(0.115)	v	V
	Boiling point: 203.7 °C Critical temperature: 431 °C Critical pressure: 3.8 MPa	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	S	185.1	124.1	62.0	(41)	(30)	V	V
BENZO-PHENONE	Chemical formula: C₁₃H₁₀O	Density, ρ_l (kg/m ³)	S	S	S	S	S	S	S	1 085	1 042	(998)	(955)	(911)	(866)
	Molecular weight: 128.21	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	S	S	S	(1.55)	(1.68)	(1.81)	(1.96)	(2.10)	(2.24)
	Melting point: 48.1 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	S	S	S	(0.136)	(0.130)	(0.124)	(0.119)	(0.113)	(0.107)
	Boiling point: 306.0 °C Critical temperature: (554) °C Critical pressure: (2.07) MPa	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	S	S	560.2	180.1	96.0	62.0	42.0	(28)

CARBOXYLIC ACIDS

			Temperature, °C												
			-150	-100	-75	-50	-25	0	20	50	100	150	200	250	300
			Temperature, K												
Substance	Data	Property	123.15	173.15	198.15	223.15	248.15	273.15	293.15	323.15	373.15	423.15	473.15	523.15	573.15
FORMIC ACID	Chemical formula: CH₂O₂	Density, ρ_l (kg/m ³)	\$	\$	\$	\$	\$	\$	1 220	1 184	1 108	V	V	V	V
	Molecular weight: 46.02	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	\$	\$	\$	\$	\$	\$	2.169	2.202	2.282	V	V	V	V
	Melting point: 8.35 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	\$	\$	\$	\$	\$	\$	0.261	0.250	0.232	V	V	V	V
	Boiling point: 100.65 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	\$	\$	\$	\$	\$	\$	179.1	103.1	54.2	V	V	V	V
	Critical temperature: 306° C														
	Critical pressure: 5.5 MPa														
ACETIC ACID	Chemical formula: C₂H₄O₂	Density, ρ_l (kg/m ³)	\$	\$	\$	\$	\$	\$	1049	1 018	960	V	V	V	V
	Molecular weight: 60.05	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	\$	\$	\$	\$	\$	\$	1.997	2.156	2.349	V	V	V	V
	Melting point: 16.7 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	\$	\$	\$	\$	\$	\$	0.161	0.155	0.142	V	V	V	V
	Boiling point: 118 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	\$	\$	\$	\$	\$	\$	121.0	79.2	45.8	V	V	V	V
	Critical temperature: 321.6 °C														
	Critical pressure: 5.79 MPa														
PROPIONIC ACID	Chemical formula: C₃H₆O₂	Density, ρ_l (kg/m ³)	\$	\$	\$	\$	\$	1 015	993	963	911	V	V	V	V
	Molecular weight: 74.08	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	\$	\$	\$	\$	\$	2.077	2.165	2.299	2.516	V	V	V	V
	Melting point: -20.65 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	\$	\$	\$	\$	\$	0.153	0.150	0.144	0.136	V	V	V	V
	Boiling point: 140.85 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	\$	\$	\$	\$	\$	154.1	169.4	73.8	45.0	V	V	V	V
	Critical temperature: 338.85 °C														
	Critical pressure: 5.37 MPa														
BUTYRIC ACID	Chemical formula: C₄H₈O₂	Density, ρ_l (kg/m ³)	\$	\$	\$	\$	\$	977	958	927	882	829	V	V	V
	Molecular weight: 88.15	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	\$	\$	\$	\$	\$	1.947	2.010	2.156	2.36	(2.64)	V	V	V
	Melting point: -5.25 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	\$	\$	\$	\$	\$	0.153	0.150	0.144	0.136	0.127	V	V	V
	Boiling point: 163.25 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	\$	\$	\$	\$	\$	228.1	154.1	98.0	55.0	34.0	V	V	V
	Critical temperature: 354.85 °C														
	Critical pressure: 5.27 MPa														

PENTANOIC ACID HEXANOIC ACID ACETIC ANHYDRIDE PROPIONIC ANHYDRIDE	Chemical formula: $C_5H_{10}O_2$	Density, ρ_l (kg/m ³)	S	S	S	S	(980)	957	942	(915)	(868)	(823)	V	V	V
	Molecular weight: 102.13	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	1.87	1.95	2.04	2.17	(2.38)	(2.60)	V	V	V
	Melting point: -34.15 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	(0.153)	0.149	0.146	0.140	0.132	0.123	V	V	V
	Boiling point: 185.55 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	(600)	355.1	223.1	131.0	66.0	(40)	V	V	V
	Critical temperature: 377.85 °C														
	Critical pressure: 3.85 MPa														
	Chemical formula: $C_6H_{12}O_2$	Density, ρ_l (kg/m ³)	S	S	S	S	S	945	929	900	(861)	(816)	(771)	V	V
	Molecular weight: 116.15	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	S	(2.09)	2.15	2.156	(2.43)	(2.60)	(2.76)	V	V
	Melting point: -3.9 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	S	0.149	0.146	0.140	0.132	0.123	0.117	V	V
	Boiling point: 205.2 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	540.2	319.9	175.0	86.0	(50)	(34)	V	V
	Critical temperature: 392 °C														
	Critical pressure: 4.0 MPa														
	Chemical formula: $C_4H_6O_3$	Density, ρ_l (kg/m ³)	S	S	S	(1161)	(1133)	1 105	1 082	1044	(979)	v	v	V	V
	Molecular weight: 102.09	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	(1.61)	(1.64)	(1.68)	(1.71)	1.750	1.905	v	V	V	V
	Melting point: -74.15 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	0.186	0.178	0.171	0.165	0.158	0.143	v	V	V	V
	Boiling point: 138.85 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	(270)	(180)	123.5	90.5	62.0	38.6	V	V	V	V
	Critical temperature: 295.85 °C														
	Critical pressure: 4.67 MPa														
	Chemical formula: $C_6H_{10}O_3$	Density, ρ_l (kg/m ³)	S	S	S	S	(1062)	(1034)	1012	978	921	864	V	V	V
	Molecular weight: 130.14	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	(1.71)	(1.74)	(1.77)	(1.83)	(1.95)	(2.10)	v	V	V
	Melting point: -45.0 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	(0.135)	(0.133)	(0.131)	(0.129)	(0.127)	(0.125)	V	V	V
	Boiling point: 167.0 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	(220)	160.0	112.0	73.1	43.0	28.0	V	V	V
	Critical temperature: 357 °C														
	Critical pressure: 3.40 MPa														

ETHERS

Substance	Data	Property	Temperature, °C												
			-150	-100	-75	-50	-25	0	20	50	100	150	200	250	300
			Temperature, K												
			123.15	173.15	198.15	223.15	248.15	273.15	293.15	323.15	373.15	423.15	473.15	523.15	573.15
DIMETHYL-ETHER	Chemical formula: C₂H₆O	Density, ρ_l (kg/m ³)	S	(846)	(812)	(773)	735	V	V	V	V	V	V	V	V
	Molecular weight: 46.07	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	2.139	2.148	2.181	2.219	V	V	V	V	V	V	V	V
	Melting point: -141.5°C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	0.228	0.211	0.194	0.178	V	V	V	V	V	V	V	V
	Boiling point: -24.85°C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	—	—	(30)	(23)	V	V	V	V	V	V	V	V
	Critical temperature: 126.85°C														
DIETHYL-ETHER	Chemical formula: C₄H₁₀O	Density, ρ_l (kg/m ³)	S	842	816	790	764	736	714	V	V	V	V	V	V
	Molecular weight: 74.12	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	2.014	2.093	2.135	2.190	2.261	2.336	V	V	V	V	V	V
	Melting point: -114.25°C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	0.180	0.170	0.159	0.150	0.140	0.138	V	V	V	V	V	V
	Boiling point: 34.65 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	171.0	88.1	55.0	38.7	29.6	24.3	V	V	V	V	V	V
	Critical temperature: 193.85°C														
METHYL-PROPYL-ETHER	Chemical formula: C₄H₁₀O	Density, ρ_l (kg/m ³)	(875)	(850)	(825)	(800)	(775)	747	(725)	V	V	V	V	V	V
	Molecular weight: 74.12	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	(1.90)	1.942	1.980	2.028	2.085	2.154	2.216	V	V	V	V	V	V
	Melting point: -150° C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	0.202	0.181	0.171	0.161	0.151	0.141	0.134	V	V	V	V	V	V
	Boiling point: 39.1 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	—	—	—	(40)	31.4	26.0	V	V	V	V	V	V
	Critical temperature: 203 °C														
ETHYL-PROPYL-ETHER	Chemical formula: C₅H₁₂O	Density, ρ_l (kg/m ³)	S	(844)	(821)	(798)	(775)	(752)	733	(704)	V	V	V	V	V
	Molecular weight: 88.15	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	1.958	2.000	2.060	2.112	2.169	2.223	(2.30)	V	V	V	V	V
	Melting point: -126.75°C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	0.170	0.161	0.152	0.144	0.136	0.129	0.120	v	V	V	V	V
	Boiling point: 63.65°C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	—	—	—	(52)	40.2	32.4	24.5	V	V	V	V	V
	Critical temperature: 227.45 °C														
METHYL-r-BUTYL-ETHER	Chemical formula: C₅H₁₂O	Density, ρ_l (kg/m ³)	S	(860)	(835)	(810)	(785)	(760)	741	(710)	v	V	V	V	V
	Molecular weight: 88.1	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	1.766	1.821	1.886	1.949	2.039	2.105	(2.22)	v	V	V	V	V
	Melting point: -110.75 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	(0.171)	(0.163)	(0.154)	(0.146)	(0.138)	(0.132)	(0.122)	v	V	V	V	V
	Boiling point: 58.05 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	—	—	(70)	(53)	(38.7)	(31.3)	(23.9)	V	V	V	V	V
	Critical temperature: 230.25 °C														
	Critical pressure: 3.411 MPa														

DIPROPYL ETHER	Chemical formula: C₆H₁₄O	Density, ρ_l (kg/m ³)	S	S	(822)	(800)	(777)	756	736	(707)	V	V	V	V	V
	Molecular weight: 102.18	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	1.825	1.892	1.968	2.052	2.119	2.244	V	V	V	V	V
	Melting point: -85.45 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	0.144	0.139	0.134	0.129	0.128	0.120	V	V	V	V	V
	Boiling point: 68.3 °C Critical temperature: 226.85 °C Critical pressure: 2.88 MPa	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	s	—	—	(72)	54.2	42.0	30.3	V	V	V	V	V
ETHYLENE OXIDE	Chemical formula: C₂H₄O	Density, ρ_l (kg/m ³)	S	(1026)	(994)	962	929	897	V	V	V	V	V	V	
	Molecular weight: 44.05	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	1.859	1.859	1.859	1.892	1.951	v	V	V	V	V	V	V
	Melting point: -112.15 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	(0.261)	(0.248)	0.235	0.222	0.208	V	V	V	V	V	V	V
	Boiling point: 10.35 °C Critical temperature: 195.85 °C Critical pressure: 7.19 MPa	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	—	(82)	57.0	40.0	32.0	V	V	V	V	V	V	V
PROPYLENE OXIDE	Chemical formula: C₃H₆O	Density, ρ_l (kg/m ³)	S	(970)	(941)	912	883	854	829	V	V	V	V	V	V
	Molecular weight: 58.08	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	1.890	1.880	1.906	1.947	1.997	2.051	V	V	V	V	V	V
	Melting point: -112.15 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	(0.205)	(0.194)	0.183	0.172	0.162	(0.153)	V	V	V	V	V	V
	Boiling point: 34.35 °C Critical temperature: 209.1 °C Critical pressure: 4.92 MPa	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	—	—	(140)	(77)	45.5	31.5	V	V	V	V	V	V
FURAN	Chemical formula: C₄H₄O	Density, ρ_l (kg/m ³)	S	S	(1040)	(1018)	(996)	965	937	V	V	V	V	V	V
	Molecular weight: 68.07	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	1.463	1.512	1.550	1.616	1.670	V	V	V	V	V	V
	Melting point: -85.65 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	(0.186)	(0.178)	(0.169)	(0.161)	(0.154)	V	V	V	V	V	V
	Boiling point: 31.35 °C Critical temperature: 217.05 °C Critical pressure: 5.50 MPa	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	s	—	(65)	(53)	(44.7)	38.2	V	V	V	V	V	V
1,4-DIOXANE	Chemical formula: C₄H₈O₂	Density, ρ_l (kg/m ³)	S	S	S	S	S	S	1 034	1008	(965)	V	V	V	V
	Molecular weight: 88.11	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	S	S	1.721	1.800	(1.96)	V	V	V	V
	Melting point: 11.1 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	S	S	0.163	(0.161)	(0.159)	V	V	V	V
	Boiling point: 101.35 °C Critical temperature: 313.85 °C Critical pressure: 5.21 MPa	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	S	126.0	77.9	(42)	V	V	V	V

HALOGENATED HYDROCARBONS

Substance	Data	Property	Temperature, °C												
			-200	-180	-160	-140	-120	-100	-50	0	20	50	100	150	200
			Temperature, K												
			73.15	93.15	113.15	133.15	153.15	173.15	223.15	273.15	293.15	323.15	373.15	423.15	473.15
CHLORO-METHANE	Chemical formula: CH_3Cl	Density, ρ_l (kg/m ³)	S	S	S	S	S	S	1 050	V	V	V	V	V	V
	Molecular weight: 50.49	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	S	S	1.499	V	V	V	V	V	V
	Melting point: -97.7°C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	S	S	0.199	V	V	V	V	V	V
	Boiling point: -24.25°C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	S	39.7	V	V	V	V	V	V
	Critical temperature: 143.15°C														
	Critical pressure: 6.68 MPa														
DICHLORO-METHANE	Chemical formula: CH_2Cl_2	Density, ρ_l (kg/m ³)	S	S	S	S	S	S	1 450	1 362	1 336	V	V	V	V
	Molecular weight: 84.93	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	S	S	1.126	1.143	1.156	V	V	V	V
	Melting point: -95.95°C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	S	S	0.163	0.148	0.141	V	V	V	V
	Boiling point: 39.85°C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	S	118	53.9	44.2	V	V	V	V
	Critical temperature: 236.85°C														
	Critical pressure: 6.08 MPa														
TRICHLORO-METHANE	Chemical formula: CHCl_3	Density, ρ_l (kg/m ³)	S	S	S	S	S	S	1 618	1 526	1490	1433	v	V	V
	Molecular weight: 119.38	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	S	S	0.959	0.971	0.992	1.034	v	V	V
	Melting point: -63.25°C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	S	S	0.156	0.145	0.128	0.115	v	V	V
	Boiling point: 61.55°C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	S	(120)	70.6	56.3	42.4	V	V	V
	Critical temperature: 263.25°C														
	Critical pressure: 5.47 MPa														
CARBON TETRA-	Chemical formula: CCl_4	Density, ρ_l (kg/m ³)	S	S	S	S	S	S	S	1 633	1 594	1534	v	V	V
	Molecular weight: 153.82	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	S	S	S	0.842	0.850	0.862	V	V	V
	Melting point: -22.9°C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	S	S	S	0.107	0.106	0.105	v	V	V
	Boiling point: 76.7°C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	S	S	134.9	96.1	65.4	V	V	V
	Critical temperature: 283.21°C														
	Critical pressure: 4.56 MPa														
BROMO-METHANE	Chemical formula: CH_3Br	Density, ρ_l (kg/m ³)	S	S	S	S	S	S	1 857	1 729	V	V	V	V	V
	Molecular weight: 94.94	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	S	S	0.816	0.829	V	V	V	V	V
	Melting point: -93.65°C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	S	S	0.114	0.103	V	V	V	V	V
	Boiling point: 3.55°C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	S	(61)	37.7	V	V	V	V	V
	Critical temperature: 190.85°C														
	Critical pressure: 6.61 MPa														

DIBROMO-METHANE	Chemical formula: CH_2Br_2	Density, ρ_l (kg/m ³)	S	S	S	S	S	S	(2680)	2 549	2 497	2 413	V	V	V
	Molecular weight: 173.84	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	S	S	0.600	0.601	0.605	0.610	V	V	V
	Melting point: -52.55°C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	S	S	0.120	0.111	0.108	0.102	V	V	V
	Boiling point: 98.65°C	Dynamic viscosity, η_l (10^{-5} Ns/m ²)	S	S	S	S	S	S	(260)	134.0	102.5	78.7	V	V	V
TRIBROMO-METHANE	Critical temperature: 309.85°C														
	Critical pressure: 7.17 MPa														
	Chemical formula: CHBr_3	Density, ρ_l (kg/m ³)	S	S	S	S	S	S	S	S	2 890	2 793	2 676	(2540)	V
	Molecular weight: 252.77	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	S	S	S	S	(0.48)	(0.50)	(0.52)	(0.56)	V
TETRA-BROMO-	Melting point: 7.9°C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	S	S	S	S	0.099	0.095	0.088	0.081	V
	Boiling point: 150.5°C	Dynamic viscosity, η_l (10^{-5} Ns/m ²)	S	S	S	S	S	S	S	S	210.9	150.0	89.5	(62)	V
	Critical temperature: 411.9°C														
	Critical pressure: 5.65 MPa														
CHLORO-DIFLUORO-METHANE (Refrigerant 22)	Chemical formula: CBr_4	Density, ρ_l (kg/m ³)	S	S	S	S	S	S	S	S	S	S	2 955	2 828	V
	Molecular weight: 331.67	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	S	S	S	S	S	S	0.452	(0.48)	V
	Melting point: 90.1°C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	S	S	S	S	S	S	0.083	0.077	V
	Boiling point: 187°C	Dynamic viscosity, η_l (10^{-5} Ns/m ²)	S	S	S	S	S	S	S	S	S	S	24.3	13.0	V
CHLORO-TRIFLUORO-METHANE (Refrigerant 13)	Critical temperature: 439°C														
	Critical pressure: 4.25 MPa														
	Chemical formula: CHClF_2	Density, ρ_l (kg/m ³)	S	S	S	S	S	1 565	1 438	V	V	V	V	V	V
	Molecular weight: 86.47	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	S	1.061	1.093	V	V	V	V	V	V
DICHLORO-FLUORO-METHANE (Refrigerant 21)	Melting point: -159.95°C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	S	0.150	0.125	V	V	V	V	V	V
	Boiling point: -40.82°C	Dynamic viscosity, η_l (10^{-5} Ns/m ²)	S	S	S	S	S	72.8	36.5	V	V	V	V	V	V
	Critical temperature: 96.15°C														
	Critical pressure: 4.986 MPa														
DIBROMO-METHANE	Chemical formula: CClF_3	Density, ρ_l (kg/m ³)	S	(1870)	(1860)	(1730)	1664	1 593	v	V	V	V	V	V	V
	Molecular weight: 104.47	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	(0.81)	(0.82)	(0.84)	(0.86)	(0.88)	v	V	V	V	V	V	V
	Melting point: -181.15°C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	0.141	0.130	0.118	0.107	0.097	v	V	V	V	V	V	V
	Boiling point: -8.14°C	Dynamic viscosity, η_l (10^{-5} Ns/m ²)	S	—	—		S	(40)	V	V	V	V	V	V	V
DIBROMO-METHANE	Critical temperature: 28.8°C														
	Critical pressure: 3.86 MPa														
	Chemical formula: CHCl_2F	Density, ρ_l (kg/m ³)	S	S	S	S	(1700)	(1624)	1 534	1 426	V	V	V	V	V
	Molecular weight: 102.92	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	0.842	0.846	0.892	1.017	V	V	V	V	V
DIBROMO-METHANE	Melting point: -135.15°C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	0.155	0.150	0.131	0.112	V	V	V	V	V
	Boiling point: 8.75°C	Dynamic viscosity, η_l (10^{-5} Ns/m ²)	S	S	S	S	(270)	186.7	72.4	39.7	V	V	V	V	V
	Critical temperature: 178.1°C														
	Critical pressure: 5.181 MPa														

HALOGENATED HYDROCARBONS (Continued)

Substance	Data	Property	Temperature, °C												
			-200	-180	-160	-140	-120	-100	-50	0	20	50	100	150	200
			Temperature, K												
			73.15	93.15	113.15	133.15	153.15	173.15	223.15	273.15	293.15	323.15	373.15	423.15	473.15
DICHLORO-DIFLUORO-METHANE (Refrigerant 12)	Chemical formula: CCl_2F_2	Density, ρ_l (kg/m ³)	S	S	S	1 798	1 743	1 688	1 546	V	V	V	V	V	V
	Molecular weight: 120.91	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	0.842	0.842	0.846	0.871	V	V	V	V	V	V
	Melting point: -155.15°C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	0.129	0.122	0.115	0.0966	V	V	V	V	V	V
	Boiling point: -29.95°C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	(130)	(100)	(80)	46.7	V	V	V	V	V	V
	Critical temperature: 111.65°C														
TRICHLORO-FLUORO-METHANE (Refrigerant 11)	Chemical formula: CCl_3F	Density, ρ_l (kg/m ³)	S	S	S	S	S	1 760	1 642	1 534	1 488	V	V	V	V
	Molecular weight: 137.37	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	S	0.800	0.829	0.862	0.883	V	V	V	V
	Melting point: -111.15°C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	S	0.123	0.109	0.0945	0.0889	V	V	V	V
	Boiling point: 23.8°C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	(210)	108.2	54.3	44.1	V	V	V	V
	Critical temperature: 198.0°C														
1,1,1-TRIFLUORO-ETHANE	Chemical formula: $\text{C}_2\text{H}_3\text{F}_3$	Density, ρ_l (kg/m ³)	S	S	S	S	S	(1300)	1 176	V	V	V	V	V	V
	Molecular weight: 84.04	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	S	1.227	1.315	V	V	V	V	V	V
	Melting point: -111.25°C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	S	0.145	0.118	V	V	V	V	V	V
	Boiling point: -47.65°C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	(43)	V	V	V	V	V	V	V
	Critical temperature: 73.05°C														
CHLORO-ETHANE	Chemical formula: $\text{C}_2\text{H}_5\text{Cl}$	Density, ρ_l (kg/m ³)	S	S	S	S	1 082	1 056	991	924	V	V	V	V	V
	Molecular weight: 64.51	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	1.344	1.486	1.495	1.566	V	V	V	V	V
	Melting point: -136.35°C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	0.164	0.158	0.143	0.128	V	V	V	V	V
	Boiling point: 12.25°C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	—	—	(50)	32.3	V	V	V	V	V
	Critical temperature: 187.25°C														
1,1-DICHLORO-ETHANE	Chemical formula: $\text{C}_2\text{H}_4\text{Cl}_2$	Density, ρ_l (kg/m ³)	S	S	S	S	S	S	(1276)	1209	1 174	(1128)	V	V	V
	Molecular weight: 98.96	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	S	S	1.226	1.257	1.276	(1.32)	V	V	V
	Melting point: -96.95°C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	S	S	0.131	0.118	0.114	0.107	V	V	V
	Boiling point: 57.25°C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	S	(120)	(61.7)	48.0	(35)	V	V	V
	Critical temperature: 249.85°C														
	Critical pressure: 5.07 MPa														

1,2-DICHLORO-ETHANE	Chemical formula: $C_2H_4Cl_2$	Density, ρ_l (kg/m ³)	S	S	S	S	S	S	S	1 287	1 258	1 209	V	V	v
	Molecular weight: 98.96	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	S	S	S	1.223	1.260	1.319	V	V	V
	Melting point: -35.65 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	S	S	S	0.140	0.135	0.128	V	V	V
	Boiling point: 83.45 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	S	S	113.7	84.0	58.4	V	V	V
1,1,1-TRICHLORO-ETHANE	Critical temperature: 287.85 °C														
	Critical pressure: 5.37 MPa														
	Chemical formula: $C_2H_3Cl_3$	Density, ρ_l (kg/m ³)	S	S	S	S	S	S	S	1 371	1 338	(1290)	V	V	V
	Molecular weight: 133.40	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	S	S	S	1.063	1.076	(1.11)	V	V	V
1,1,2,2-TETRA-CHLORO-ETHANE	Melting point: -33.0 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	S	S	S	0.106	0.102	0.096	V	V	V
	Boiling point: 74.0 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	S	S	(130)	84.0	(48)	V	V	V
	Critical temperature: 255 °C														
	Critical pressure: 4.15 MPa														
PENTA-CHLORO-ETHANE	Chemical formula: $C_2H_2Cl_4$	Density, ρ_l (kg/m ³)	S	S	S	S	S	S	S	1 633	1600	(1550)	(1470)	V	V
	Molecular weight: 167.88	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	S	S	S	0.944	0.952	0.973	0.985	V	V
	Melting point: -42.5 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	S	S	S	0.118	0.114	0.108	0.099	V	V
	Boiling point: 146.2 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	S	S	265.7	177.0	113.2	62.0	V	V
BROMO-ETHANE	Critical temperature: 377° C														
	Critical pressure: 5.13 MPa														
	Chemical formula: C_2H_5Br	Density, ρ_l (kg/m ³)	S	S	S	S	S	S	S	1709	1 678	(1630)	(1555)	(1480)	V
	Molecular weight: 108.97	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	S	S	S	(0.85)	(0.86)	(0.87)	(0.89)	(0.92)	V
1,2-DIBROMO-ETHANE	Melting point: -118.55 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	S	S	S	0.104	0.100	0.095	0.086	0.077	V
	Boiling point: 38.35 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	S	S	(390)	258	(180)	(110)	(80)	V
	Critical temperature: 230.65 °C														
	Critical pressure: 6.23 MPa														
1,2-DIBROMO-ETHANE	Chemical formula: $C_2H_4Br_2$	Density, ρ_l (kg/m ³)	S	S	S	S	S	S	S	1 697	1 600	1 501	1 462	V	V
	Molecular weight: 187.87	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	S	S	S	0.816	0.846	0.888	0.909	V	V
	Melting point: 10.0 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	S	S	S	0.126	0.115	0.105	0.100	V	V
	Boiling point: 13 1.7 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	S	S	289	185	81	39.6	V	V
1,2-DIBROMO-ETHANE	Critical temperature: 377° C														
	Critical pressure: 5.69 MPa														
	Chemical formula: $C_2H_4Br_2$	Density, ρ_l (kg/m ³)	S	S	S	S	S	S	S	2 180	2 118	(2040)	V	V	V
	Molecular weight: 187.87	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	S	S	S	0.729	0.733	(0.77)	V	V	V
1,2-DIBROMO-ETHANE	Melting point: 10.0 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	S	S	S	0.102	0.098	0.089	V	V	V
	Boiling point: 13 1.7 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	S	S	173	115.2	64.4	V	V	V
	Critical temperature: 377° C														
	Critical pressure: 5.69 MPa														

HALOGENATED HYDROCARBONS (Continued)

			Temperature, °C												
			-200	-180	-160	-140	-120	-100	-50	0	20	50	100	150	200
			Temperature, K												
Substance	Data	Property	73.15	93.15	113.15	133.15	153.15	173.15	223.15	273.15	293.15	323.15	373.15	423.15	473.15
TETRA- CHLORO- DIFLUORO- ETHANE	Chenucal formula: C ₂ Cl ₄ F ₂	Density, ρ _l (kg/m ³)	S	S	S	S	S	S	S	S	S	(1596)	V	V	V
	Molecular weight: 203.83	Specific heat capacity, c _{p,l} (kJ/kg K)	S	S	S	S	S	S	S	S	S	(0.91)	V	V	V
	Melting point: 24.85 °C	Thermal conductivity, λ _l [(W/m ²)/(K/m)]	S	S	S	S	S	S	S	S	S	0.078	V	V	V
	Boiling point: 93 °C	Dynamic viscosity, η _l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	S	S	S	S	90.8	V	V	V
	Critical temperature: 278 °C														
TRICHLORO- TRIFLUORO- ETHANE (Refrigerant 113)	Chenucal formula: C ₂ Cl ₃ F ₃	Density, ρ _l (kg/m ³)	S	S	S	S	S	S	S	1 621	1 575	V	V	V	V
	Molecular weight: 187.38	Specific heat capacity, c _{p,l} (kJ/kg K)	S	S	S	S	S	S	S	0.858	0.900	V	V	V	V
	Melting point: -34.96 °C	Thermal conductivity, λ _l [(W/m ²)/(K/m)]	S	S	S	S	S	S	S	0.0802	0.0761	V	V	V	V
	Boiling point: 47.6 °C	Dynamic viscosity, η _l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	S	S	97.8	72.7	V	V	V	V
	Critical temperature: 214.1 °C														
DICHLORO- TETRA- FLUORO- ETHANE (Refrigerant 114)	Chemical formula: C ₂ Cl ₂ F ₄	Density, ρ _l (kg/m ³)	S	S	S	S	S	S	1 678	1 538	V	V	V	V	V
	Molecular weight: 170.92	Specific heat capacity, c _{p,l} (kJ/kg K)	S	S	S	S	S	S	0.929	0.963	V	V	V	V	V
	Melting point: -93.85 °C	Thermal conductivity, λ _l [(W/m ²)/(K/m)]	S	S	S	S	S	S	0.0841	0.0710	V	V	V	V	V
	Boiling point: 3.75 °C	Dynamic viscosity, η _l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	S	107.2	46.7	V	V	V	V	V
	Critical temperature: 145.75 °C														
CHLORO- PROPANE	Chemical formula: C ₃ H ₇ Cl	Density, ρ _l (kg/m ³)	S	S	S	S	S	(1036)	(975)	916	890	V	V	V	V
	Molecular weight: 78.54	Specific heat capacity, c _{p,l} (kJ/kg K)	S	S	S	S	S	(1.50)	(1.55)	1.574	1.650	V	V	V	V
	Melting point: -122.75 °C	Thermal conductivity, λ _l [(W/m ²)/(K/m)]	S	S	S	S	S	0.147	0.135	0.122	0.117	V	V	V	V
	Boiling point: 46.45 °C	Dynamic viscosity, η _l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	—	(74)	40.5	32.9	V	V	V	V
	Critical temperature: 229.85 °C														
CHLORO- BUTANE	Chenucal formula: C ₄ H ₉ Cl	Density, ρ _l (kg/m ³)	S	S	S	S	S	S	S	907	897	852	V	V	V
	Molecular weight: 92.57	Specific heat capacity, c _{p,l} (kJ/kg K)	S	S	S	S	S	S	S	1.69	1.74	1.80	V	V	V
	Melting point: -25.35 °C	Thermal conductivity, λ _l [(W/m ²)/(K/m)]	S	S	S	S	S	S	S	0.122	0.118	0.111	V	V	V
	Boiling point: 50.8 °C	Dynamic viscosity, η _l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	S	S	(54)	44.0	32.8	V	V	V
	Critical temperature: 233.85 °C														
	Critical pressure: 3.95 MPa														

CHLORO-PENTANE	Chemical formula: $C_5H_{11}Cl$	Density, ρ_l (kg/m ³)	S	S	S	S	S	S	(951)	902	882	853	(803)	V	V
	Molecular weight: 106.59	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	S	S	(1.60)	(1.71)	(1.77)	(1.86)	(2.00)	V	V
	Melting point: $-99.0^\circ C$	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	S	S	0.135	0.124	0.120	0.113	0.103	V	V
	Boiling point: $108.3^\circ C$	Dynamic viscosity, η_l (10^{-5} Ns/m ²)	S	S	S	S	S	S	(122)	(72)	58.0	(43)	(29)	V	V
	Critical temperature: $289^\circ C$														
VINYL CHLORIDE	Chemical formula: C_2H_3Cl	Density, ρ_l (kg/m ³)	S	S	S	(1192)	(1156)	(1120)	(1031)	V	V	V	V	V	V
	Molecular weight: 62.60	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	1.363	1.359	1.356	1.358	V	V	V	V	V	V
	Melting point: $-153.75^\circ C$	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	0.168	0.161	0.154	0.138	V	V	V	V	V	V
	Boiling point: $-13.35^\circ C$	Dynamic viscosity, η_l (10^{-5} Ns/m ²)	S	S	S	—	—	—	(43)	V	V	V	V	V	V
	Critical temperature: $156.55^\circ C$														
1,1-DICHLORO-ETHYLENE	Chemical formula: $C_2H_2Cl_2$	Density, ρ_l (kg/m ³)	S	S	S	S	(1494)	(1412)	(1330)	(1248)	(1213)	V	V	V	V
	Molecular weight: 96.95	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	1.027	1.034	1.065	1.117	1.172	V	V	V	V
	Melting point: $-122.5^\circ C$	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	0.146	0.140	0.127	0.113	0.108	V	V	V	V
	Boiling point: $31.7^\circ C$	Dynamic viscosity, η_l (10^{-5} Ns/m ²)	S	S	S	S		(220)	116	57.8	46.7	V	V	V	V
	Critical temperature: $215.9^\circ C$														
TRICHLORO-ETHYLENE	Chemical formula: C_2HCl_3	Density, ρ_l (kg/m ³)	S	S	S	S	S	S	1660	1 550	1 463	1440	V	V	V
	Molecular weight: 131.39	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	S	S	0.900	0.938	0.950	(0.98)	V	V	V
	Melting point: $-87.0^\circ C$	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	S	S	0.133	0.121	0.116	0.110	V	V	V
	Boiling point: $87.25^\circ C$	Dynamic viscosity, η_l (10^{-5} Ns/m ²)	S	S	S	S	S	S	140	71.0	60.0	44.7	V	V	V
	Critical temperature: $297.85^\circ C$														
TETRA-CHLORO-ETHYLENE	Chemical formula: C_2Cl_4	Density, ρ_l (kg/m ³)	S	S	S	S	S	S	S	1 656	1 621	1 574	1490	V	V
	Molecular weight: 165.83	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	S	S	S	0.829	0.879	0.946	1.043	V	V
	Melting point: $-22.15^\circ C$	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	S	S	S	0.114	0.110	0.104	0.094	V	V
	Boiling point: $121.15^\circ C$	Dynamic viscosity, η_l (10^{-5} Ns/m ²)	S	S	S	S	S	S	S	114.4	90.4	65.7	45.4	V	V
	Critical temperature: $346.85^\circ C$														
FLUORO-BENZENE	Chemical formula: C_6H_5F	Density, ρ_l (kg/m ³)	S	S	S	S	S	S	S	1047	1 024	985	V	V	V
	Molecular weight: 96.10	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	S	S	S	1.503	1.524	1.570	V	V	V
	Melting point: $-39.15^\circ C$	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	S	S	S	0.133	0.127	0.119	V	V	V
	Boiling point: $85.35^\circ C$	Dynamic viscosity, η_l (10^{-5} Ns/m ²)	S	S	S	S	S	S	S	75.4	59.8	42.8	V	V	V
	Critical temperature: $286.95^\circ C$														
FLUORO-BENZENE	Chemical formula: C_6H_5F	Density, ρ_l (kg/m ³)	S	S	S	S	S	S	S	1047	1 024	985	V	V	V
	Molecular weight: 96.10	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	S	S	S	1.503	1.524	1.570	V	V	V
	Melting point: $-39.15^\circ C$	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	S	S	S	0.133	0.127	0.119	V	V	V
	Boiling point: $85.35^\circ C$	Dynamic viscosity, η_l (10^{-5} Ns/m ²)	S	S	S	S	S	S	S	75.4	59.8	42.8	V	V	V
	Critical temperature: $286.95^\circ C$														
FLUORO-BENZENE	Chemical formula: C_6H_5F	Density, ρ_l (kg/m ³)	S	S	S	S	S	S	S	1047	1 024	985	V	V	V
	Molecular weight: 96.10	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	S	S	S	1.503	1.524	1.570	V	V	V
	Melting point: $-39.15^\circ C$	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	S	S	S	0.133	0.127	0.119	V	V	V
	Boiling point: $85.35^\circ C$	Dynamic viscosity, η_l (10^{-5} Ns/m ²)	S	S	S	S	S	S	S	75.4	59.8	42.8	V	V	V
	Critical temperature: $286.95^\circ C$														

HALOGENATED HYDROCARBONS (Continued)

			Temperature, °C												
			-200	-180	-160	-140	-120	-100	-50	0	20	50	100	150	200
			Temperature, K												
Substance	Data	Property	73.15	93.15	113.15	133.15	153.15	173.15	223.15	273.15	293.15	323.15	373.15	423.15	473.15
CHLORO-BENZENE	Chemical formula: C ₆ H ₅ Cl	Density, ρ _l (kg/m ³)	S	S	S	S	S	S	S	1 128	1 106	1 074	1 019	V	V
	Molecular weight: 112.56	Specific heat capacity, c _{p,l} (kJ/kg K)	S	S	S	S	S	S	S	1.264	1.298	1.348	1.507	V	V
	Melting point: −45.55 °C	Thermal conductivity, λ _l [(W/m ²)/(K/m)]	S	S	S	S	S	S	S	0.133	0.129	0.122	0.112	V	V
	Boiling point: 131.75 °C	Dynamic viscosity, η _l (10 ^{−5} Ns/m ²)	S	S	S	S	S	S	S	105	80	58	37	V	V
	Critical temperature: 359.25 °C														
	Critical pressure: 4.52 MPa														
BROMO-BENZENE	Chemical formula: C ₆ H ₅ Br	Density, ρ _l (kg/m ³)	S	S	S	S	S	S	S	1 522	1 495	1 455	1 386	1 315	V
	Molecular weight: 157.01	Specific heat capacity, c _{p,l} (kJ/kg K)	S	S	S	S	S	S	S	0.950	0.963	0.988	1.068	(1.12)	V
	Melting point: −30.7 °C	Thermal conductivity, λ _l [(W/m ²)/(K/m)]	S	S	S	S	S	S	S	0.116	0.112	0.106	0.098	0.088	V
	Boiling point: 156.2 °C	Dynamic viscosity, η _l (10 ^{−5} Ns/m ²)	S	S	S	S	S	S	S	156.4	112.4	80.0	51.8	(34)	V
	Critical temperature: 397 °C														
	Critical pressure: 4.56 MPa														
IODO-BENZENE	Chemical formula: C ₆ H ₅ I	Density, ρ _l (kg/m ³)	S	S	S	S	S	S	S	1 861	1 832	1 785	1 708	1 627	V
	Molecular weight: 204.01	Specific heat capacity, c _{p,l} (kJ/kg K)	S	S	S	S	S	S	S	0.770	0.775	0.791	(0.84)	(0.87)	V
	Melting point: -3 1.35 °C	Thermal conductivity, λ _l [(W/m ²)/(K/m)]	S	S	S	S	S	S	S	0.103	0.101	0.098	0.092	0.081	V
	Boiling point: 188.25 °C	Dynamic viscosity, η _l (10 ^{−5} Ns/m ²)	S	S	S	S	S	S	S	242	170.5	112.1	69.0	(41)	V
	Critical temperature: 447.85 °C														
	Critical pressure: 4.52 MPa														
BENZYL CHLORIDE	Chemical formula: C ₇ H ₇ Cl	Density, ρ _l (kg/m ³)	S	S	S	S	S	S	S	1 103	1 082	(1053)	(1003)	(954)	V
	Molecular weight: 126.58	Specific heat capacity, c _{p,l} (kJ/kg K)	S	S	S	S	S	S	S	1.403	1.432	1.495	1.675	(1.88)	V
	Melting point: −39.2 °C	Thermal conductivity, λ _l [(W/m ²)/(K/m)]	S	S	S	S	S	S	S	0.141	0.137	0.131	0.120	0.110	V
	Boiling point: 179.4 °C	Dynamic viscosity, η _l (10 ^{−5} Ns/m ²)	S	S	S	S	S	S	S	(180)	138.0	(96)	(56)	(40)	V
	Critical temperature: 412° C														
	Critical pressure: 3.85 MPa														
m-CHLORO-TOLUENE	Chemical formula: C ₇ H ₇ Cl	Density, ρ _l (kg/m ³)	S	S	S	S	S	S	S	1 088	1 072	1 038	987	937	V
	Molecular weight: 126.58	Specific heat capacity, c _{p,l} (kJ/kg K)	S	S	S	S	S	S	S	(1.35)	(1.39)	(1.46)	(1.58)	(1.70)	V
	Melting point: −47.8 °C	Thermal conductivity, λ _l [(W/m ²)/(K/m)]	S	S	S	S	S	S	S	0.130	0.126	0.120	0.110	0.100	V
	Boiling point: 161.6 °C	Dynamic viscosity, η _l (10 ^{−5} Ns/m ²)	S	S	S	S	S	S	S	117.7	87.7	61.6	39.2	27.8	V
	Critical temperature: 389° C														
	Critical pressure: 3.85 MPa														

AMINES

			Temperature, °C												
			-150	-100	-75	-50	-25	0	20	50	100	150	200	250	300
			Temperature, K												
Substance	Data	Property	123.15	173.15	198.15	223.15	248.15	273.15	293.15	323.15	373.15	423.15	473.15	523.15	573.15
METHYL-AMINE	Chemical formula: CH ₅ N	Density, ρ _l (kg/m ³)	S	S	769	740	712	V	V	V	V	V	V	V	V
	Molecular weight: 31.06	Specific heat capacity, c _{p,l} (kJ/kg K)	S	S	3.207	3.236	3.282	V	V	V	V	V	V	V	V
	Melting point: -93.45 °C	Thermal conductivity, λ _l [(W/m ²)/(K/m)]	S	S	0.233	0.224	0.216	V	V	V	V	V	V	V	V
	Boiling point: -6.35 °C	Dynamic viscosity, η _l (10 ⁻⁵ Ns/m ²)	S	S	0.233	0.224	0.216	V	V	V	V	V	V	V	V
	Critical temperature: 156.85 °C														
DIMETHYL-AMINE	Critical pressure: 7.46 MPa														
	Chemical formula: C ₂ H ₇ N	Density, ρ _l (kg/m ³)	S	S	(763)	(735)	(707)	679	V	V	V	V	V	V	V
	Molecular weight: 45.08	Specific heat capacity, c _{p,l} (kJ/kg K)	S	S	2.797	2.935	2.989	3.023	V	V	V	V	V	V	V
	Melting point: -92.15 °C	Thermal conductivity, λ _l [(W/m ²)/(K/m)]	S	S	0.181	0.171	0.160	0.151	v	V	V	V	V	V	V
	Boiling point: 6.85 °C	Dynamic viscosity, η _l (10 ⁻⁵ Ns/m ²)	S	S	0.181	0.171	0.160	0.151	v	V	V	V	V	V	V
TRIMETHYL-AMINE	Critical temperature: 164.45 °C														
	Critical pressure: 5.31 MPa														
	Chemical formula: C ₃ H ₉ N	Density, ρ _l (kg/m ³)	S	(767)	(740)	(713)	685	658	V	V	V	V	V	V	V
	Molecular weight: 59.11	Specific heat capacity, c _{p,l} (kJ/kg K)	S	1.964	1.989	2.052	2.131	2.223	V	V	V	V	V	V	V
	Melting point: -117.15 °C	Thermal conductivity, λ _l [(W/m ²)/(K/m)]	S	0.168	0.157	0.146	0.135	0.126	V	V	V	V	V	V	V
ETHYL-AMINE	Boiling point: 2.95 °C	Dynamic viscosity, η _l (10 ⁻⁵ Ns/m ²)	S												
	Critical temperature: 160.05 °C														
	Critical pressure: 4.07 MPa														
	Chemical formula: C ₂ H ₇ N	Density, ρ _l (kg/m ³)	S	S	(788)	761	734	707	v	V	V	V	V	V	V
	Molecular weight: 45.08	Specific heat capacity, c _{p,l} (kJ/kg K)	S	S	(2.91)	(2.95)	(2.99)	(3.03)	v	V	V	V	V	V	V
DIETHYL-AMINE	Melting point: -81.15 °C	Thermal conductivity, λ _l [(W/m ²)/(K/m)]	S	S	0.212	0.204	0.197	0.191	v	V	V	V	V	V	V
	Boiling point: 16.55 °C	Dynamic viscosity, η _l (10 ⁻⁵ Ns/m ²)	S	S											
	Critical temperature: 182.85 °C														
	Critical pressure: 5.62 MPa														
	Chemical formula: C ₄ H ₁₁ N	Density, ρ _l (kg/m ³)	S	S	S	S	(756)	730	709	677	V	V	V	V	V
DIETHYL-AMINE	Molecular weight: 73.14	Specific heat capacity, c _{p,l} (kJ/kg K)	S	S	S	S	(2.27)	(2.35)	2.417	2.525	V	V	V	V	V
	Melting point: -48.00 °C	Thermal conductivity, λ _l [(W/m ²)/(K/m)]	S	S	S	S	0.149	0.141	0.135	0.127	V	V	V	V	V
	Boiling point: 55.45 °C	Dynamic viscosity, η _l (10 ⁻⁵ Ns/m ²)	S	S	S	S	75.4	44.0	33.0	24.0	V	V	V	V	V
	Critical temperature: 223.45 °C														
	Critical pressure: 3.71 MPa														

AMINES (Continued)

			Temperature, °C												
			-150	-100	-75	-50	-25	0	20	50	100	150	200	250	300
			Temperature, K												
Substance	Data	Property	123.15	173.15	198.15	223.15	248.15	273.15	293.15	323.15	373.15	423.15	473.15	523.15	573.15
TRIETHYL-AMINE	Chemical formula: C ₆ H ₁₅ N	Density, ρ _l (kg/m ³)	S	(830)	(810)	(789)	768	746	726	699	V	V	V	V	V
	Molecular weight: 101.19	Specific heat capacity, c _{p,l} (kJ/kg K)	S	(1.56)	(1.70)	(1.79)	(1.88)	2.092	2.208	2.367	V	V	V	V	V
	Melting point: -114.75 °C	Thermal conductivity, λ _l [(W/m ²)/(K/m)]	S	0.151	0.145	0.140	0.133	0.126	0.121	0.111	V	V	V	V	V
	Boiling point: 89.55 °C	Dynamic viscosity, η _l (10 ⁻⁵ Ns/m ²)	S	—	(150)	(102)	70.5	51.0	36.2	27.0	V	V	V	V	V
	Critical temperature: 261.85 °C														
ISOPROPYL-AMINE	Critical pressure: 3.03 MPa														
	Chemical formula: C ₃ H ₉ N	Density, ρ _l (kg/m ³)	S	S	(822)	(796)	(768)	(740)	719	V	V	V	V	V	V
	Molecular weight: 59.11	Specific heat capacity, c _{p,l} (kJ/kg K)	S	S	2.507	2.642	2.690	2.737	2.770	V	V	V	V	V	V
	Melting point: -95.25 °C	Thermal conductivity, λ _l [(W/m ²)/(K/m)]	S	S	0.161	0.155	0.150	0.146	0.143	V	V	V	V	V	V
	Boiling point: 32.45 °C	Dynamic viscosity, η _l (10 ⁻⁵ Ns/m ²)	S	S	—	—	(67)	46.05	35.0	V	V	V	V	V	V
PIPERIDINE	Critical temperature: 202.85 °C														
	Critical pressure: 5.07 MPa														
	Chemical formula: C ₅ H ₁₁ Cl	Density, ρ _l (kg/m ³)	S	S	S	S	S	880	861	834	787	V	V	V	V
	Molecular weight: 85.15	Specific heat capacity, c _{p,l} (kJ/kg K)	S	S	S	S	S	(2.09)	2.136	2.202	(2.33)	V	V	V	V
	Melting point: -10.45 °C	Thermal conductivity, λ _l [(W/m ²)/(K/m)]	S	S	S	S	S	0.131	0.125	0.118	0.105	V	V	V	V
PYRIDINE	Boiling point: 106.55 °C	Dynamic viscosity, η _l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	(400)	148.6	84.5	47.5	V	V	V	V
	Critical temperature: 320.85 °C														
	Critical pressure: 4.76 MPa														
	Chemical formula: C ₅ H ₅ N	Density, ρ _l (kg/m ³)	S	S	S	S	1 028	1003	983	953	901	V	V	V	V
	Molecular weight: 79.10	Specific heat capacity, c _{p,l} (kJ/kg K)	S	S	S	S	(1.60)	1.645	1.696	1.767	(1.90)	V	V	V	V
PYRIDINE	Melting point: -41.65 °C	Thermal conductivity, λ _l [(W/m ²)/(K/m)]	S	S	S	S	(0.176)	0.168	0.162	0.152	0.138	V	V	V	V
	Boiling point: 115.35 °C	Dynamic viscosity, η _l (10 ⁻⁵ Ns/m ²)	S	S	S	S	(223)	136	95.8	63.9	40.0	V	V	V	V
	Critical temperature: 356.85 °C														
PYRIDINE	Critical pressure: 5.63 MPa														

ANILINE	Chemical formula: C_6H_7N	Density, ρ_l (kg/m ³)	S	S	S	S	S	1 039	1 022	996	951	905	V	V	V
	Molecular weight: 93.06	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	S	2.030	2.068	2.121	2.209	2.293	V	V	V
	Melting point: -6.1 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	S	0.200	0.195	0.174	0.167	0.159	V	V	V
	Boiling point: 184.4 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	1 020	440	185	82	49	V	V	V
	Critical temperature: 425.85 °C														
	Critical pressure: 5.301 MPa														
METHYL-ANILINE	Chemical formula: C_7H_9N	Density, ρ_l (kg/m ³)	S	S	S	(1042)	(1022)	1002	986	963	922	880	V	V	V
	Molecular weight: 107.15	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	(1.98)	(2.00)	(2.02)	(2.04)	(2.07)	2.127	(2.19)	V	V	V
	Melting point: -57 .0 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	0.173	0.167	0.163	0.159	0.153	0.143	0.134	V	V	V
	Boiling point: 196.3 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S		(920)	435.1	230	124	63.1	39.1	V	V	V
	Critical temperature: 428.6 °C														
DIMETHYL-ANILINE	Chemical formula: $C_8H_{11}N$	Density, ρ_l (kg/m ³)	S	S	S	S	S	S	956	930	891	850	V	V	V
	Molecular weight: 121.18	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	S	S	1.792	1.876	2.022	(2.14)	V	V	V
	Melting point: -2.45 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	S	S	0.143	0.138	0.129	0.120	V	V	V
	Boiling point: 193.55 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	S	138.7	91.0	57.2	35.0	V	V	V
	Critical temperature: 413.85 °C														
DIETHYL-ANILINE	Chemical formula: $C_{10}H_{15}N$	Density, ρ_l (kg/m ³)	S	S	S	S	S	951	935	910	871	832	(798)	V	V
	Molecular weight: 149.24	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	S	(1.77)	(1.82)	2.010	2.024	(2.16)	(2.33)	V	V
	Melting point: -21.3 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	S	0.140	0.137	0.132	0.129	0.120	0.112	V	V
	Boiling point: 217.1 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	390.1	218.6	119.1	62.6	40.7	29.0	V	V
	Critical temperature: 422 °C														
	Critical pressure: 3.2 MPa														

NITRILES															
			Temperature, °C												
			-150	-100	-75	-50	-25	0	20	50	100	150	200	250	300
			Temperature, K												
Substance	Data	Property	123.15	173.15	198.15	223.15	248.15	273.15	293.15	323.15	373.15	423.15	473.15	523.15	573.15
ACETON-NITRILE	Chemical formula: C ₂ H ₃ N	Density, ρ_l (kg/m ³)	S	S	S	S	829	803	783	750	v	V	V	V	V
	Molecular weight: 41.05	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	2.17	2.20	2.256	2.361	V	V	V	V	V
	Melting point: -43.85 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	0.227	0.218	0.211	0.201	v	V	V	V	V
	Boiling point: 81.65 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	(63)	44.5	26.0	27.2	V	V	V	V	V
	Critical temperature: 274.85 °C														
PROPIO-NITRILE	Critical pressure: 4.83 MPa														
	Chemical formula: C ₃ H ₅ N	Density, ρ_l (kg/m ³)	S	S	(874)	850	826	802	782	750	v	V	V	V	V
	Molecular weight: 55.08	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	2.012	2.036	2.069	2.117	2.163	2.251	V	V	V	V	V
	Melting point: -92.85 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	0.200	0.192	0.185	0.177	0.172	0.164	v	V	V	V	V
	Boiling point: 97.35 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	s	—	(113)	(79)	54.1	43.2	32.7	V	V	V	V	V
BUTYRO-NITRILE	Critical temperature: 291.25 °C														
	Critical pressure: 4.48 MPa														
	Chemical formula: C ₄ H ₇ N	Density, ρ_l (kg/m ³)	S	(905)	(881)	(857)	(833)	809	790	761	712	V	V	V	V
	Molecular weight: 69.11	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	(2.05)	(2.07)	(2.08)	(2.10)	(2.12)	(2.14)	2.219	(2.33)	V	V	V	V
	Melting point: -112.15 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	0.186	0.178	0.172	0.166	0.159	0.154	0.148	0.137	V	V	V	V
	Boiling point: 117.85 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	0.186	0.178	0.172	0.166	0.159	0.154	0.148	0.137	V	V	V	V
	Critical temperature: 309.05 °C														
	Critical pressure: 3.79 MPa														

AMIDES															
			- 150	- 100	- 75	- 50	- 25	0	Temperature, 20	50 °C	100	150	200	250	300
Substance	Data	Property	123.15	173.15	198.15	223.15	248.15	273.15	Temperature, 293.15	323.15 K	373.15	423.15	473.15	523.15	573.15
FOBMAMIDE	Chemical formula: CH₃NO	Density, ρ_l (kg/m ³)	S	S	S	S	S	S	1.112	(1100)	(1070)	(1020)	(980)	V	V
	Molecular weight: 45.04	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	S	S	2.382	2.412	(2.56)	(2.67)	(2.74)	V	V
	Melting point: 2.2 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	S	S	0.362	0.352	(0.335)	(0.318)	(0.301)	V	V
	Boiling point: 210.5 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	S	376.4	184.0	85.1	(44)	(23)	V	V
	Critical temperature: 472 °C														
Critical pressure: 9.5 MPa															



NITRO DERIVATIVES

			Temperature, °C												
			-150	-100	-75	-50	-25	0	20	50	100	150	200	250	300
			Temperature, K												
Substance	Data	Property	123.15	173.15	198.15	223.15	248.15	273.15	293.15	323.15	373.15	423.15	473.15	523.15	573.15
NITRO-METHANE	Chemical formula: CH ₃ NO ₂	Density, ρ _l (kg/m ³)	S	S	S	S	(1198)	(1164)	1136	1095	1026	V	V	V	V
	Molecular weight: 61.04	Specific heat capacity, c _{p,l} (kJ/kg K)	S	S	S	S	(1.66)	(1.70)	1.729	1.775	1.861	V	V	V	V
	Melting point: -28.55 °C	Thermal conductivity, λ _l [(W/m ²)/(K/m)]	S	S	S	S	0.217	0.210	0.204	0.194	0.179	V	V	V	V
	Boiling point: 101.25 °C	Dynamic viscosity, η _l (10 ⁻⁵ Ns/m ²)	S	S	S	S	(115)	84.4	65.7	47.9	29.8	V	V	V	V
	Critical temperature: 314.85 °C														
	Critical pressure: 6.31 MPa														
NITRO-BENZENE	Chemical formula: C ₆ H ₅ NO ₂	Density, ρ _l (kg/m ³)	S	S	S	S	S	S	1204	1 174	1 124	1 073	1 020	V	V
	Molecular weight: 123.11	Specific heat capacity, c _{p,l} (kJ/kg K)	S	S	S	S	S	S	1.465	1.507	1.617	(1.77)	(1.85)	V	V
	Melting point: 5.7 °C	Thermal conductivity, λ _l [(W/m ²)/(K/m)]	S	S	S	S	S	S	0.149	0.146	0.138	0.130	0.117	V	V
	Boiling point: 210.9 °C	Dynamic viscosity, η _l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	S	201.0	124.1	70.0	50.5	39.0	V	V
	Critical temperature: 439° C														
	Critical pressure: 3.5 MPa														
o-NITRO-TOLUENE	Chemical formula: C ₇ H ₇ NO ₂	Density, ρ _l (kg/m ³)	S	S	S	S	S	(1180)	1 163	1 132	1 082	1 034	985	V	V
	Molecular weight: 137.13	Specific heat capacity, c _{p,l} (kJ/kg K)	S	S	S	S	S	1.072	1.139	1.252	1.432	1.641	(1.86)	V	V
	Melting point: -3.2 °C	Thermal conductivity, λ _l [(W/m ²)/(K/m)]	S	S	S	S	S	0.144	0.141	0.136	0.128	0.120	0.112	V	V
	Boiling point: 22 1.7 °C	Dynamic viscosity, η _l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	383.1	237.0	142.0	74.2	47.8	33.0	V	V
	Critical temperature: 447 °C														
	Critical pressure: 3.4 MPa														
m-NITRO-TOLUENE	Chemical formula: C ₇ H ₇ NO ₂	Density, ρ _l (kg/m ³)	S	S	S	S	S	S	1 157	(1130)	(1082)	(1036)	(988)	V	V
	Molecular weight: 137.13	Specific heat capacity, c _{p,l} (kJ/kg K)	S	S	S	S	S	S	1.097	1.227	(1.40)	1.60)	(1.83)	V	V
	Melting point: 16.1 °C	Thermal conductivity, λ _l [(W/m ²)/(K/m)]	S	S	S	S	S	S	0.141	0.136	0.128	0.120	0.112	V	V
	Boiling point: 232.6 °C	Dynamic viscosity, η _l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	S	233.1	139.8	75.0	(46)	(27)	V	V
	Critical temperature: 452 °C														
	Critical pressure: 3.1 MPa														
p-NITRO-TOLUENE	Chemical formula: C ₇ H ₇ NO ₂	Density, ρ _l (kg/m ³)	S	S	S	S	S	S	S	S	1 082	1 036	988	V	V
	Molecular weight: 137.13	Specific heat capacity, c _{p,l} (kJ/kg K)	S	S	S	S	S	S	S	S	1.357	1.453	1.687	V	V
	Melting point: 51.8 °C	Thermal conductivity, λ _l [(W/m ²)/(K/m)]	S	S	S	S	S	S	S	S	0.137	0.128	0.120	V	V
	Boiling point: 238.6 °C	Dynamic viscosity, η _l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	S	S	S	76.0	48.2	34.7	V	V
	Critical temperature: 462 °C														
	Critical pressure: 3.0 MPa														

ORGANIC SULFUR COMPOUNDS

			Temperature, °C												
			-200	-180	—160	-140	-120	-100	-50	0	20	50	100	150	200
			Temperature, K												
Substance	Data	Property	73.15	93.15	113.15	133.15	153.15	173.15	223.15	273.15	293.15	323.15	373.15	423.15	473.15
METHYL- MERCAPTAN	Chemical formula: CH ₄ S	Density, ρ _l (kg/m ³)	S	S	S	S	(1046)	(1019)	(957)	(895)	V	V	V	V	V
	Molecular weight: 48.11	Specific heat capacity, c _{p,l} (kJ/kg K)	S	S	S	S	(1.84)	1.825	1.800	1.842	V	V	V	V	V
	Melting point: -122 °C	Thermal conductivity, λ _l [(W/m ²)/(K/m)]	S	S	S	S	—	—	(0.247)	(0.207)	V	V	V	V	V
	Boiling point: 6.8 °C	Dynamic viscosity, η _l (10 ⁻⁵ Ns/m ²)	S	S	S	S	—	—	(49)	(29)	V	V	V	V	V
	Critical temperature: 196.8 °C														
ETHYL- MERCAPTAN	Chemical formula: C ₂ H ₆ S	Density, ρ _l (kg/m ³)	S	S	S	(994)	(972)	(950)	(896)	842	820	V	V	V	V
	Molecular weight: 62.13	Specific heat capacity, c _{p,l} (kJ/kg K)	S	S	S	1.840	1.815	1.805	1.803	1.851	1.885	V	V	V	V
	Melting point: -147° C	Thermal conductivity, λ _l [(W/m ²)/(K/m)]	S	S	S	—	—		(0.172)	(0.143)	0.133	V	V	V	V
	Boiling point: 34.4 °C	Dynamic viscosity, η _l (10 ⁻⁵ Ns/m ²)	S	S	S	—	—	—	(62)	36.3	30.0	V	V	V	V
	Critical temperature: 225.5 °C														
DIMETHYL- SULFIDE	Chemical formula: C ₂ H ₆ S	Density, ρ _l (kg/m ³)	S	S	S	S	S	S	(931)	872	850	V	V	V	V
	Molecular weight: 62.13	Specific heat capacity, c _{p,l} (kJ/kg K)	S	S	S	S	S	S	1.813	1.863	1.897	V	V	V	V
	Melting point: -98.3 °C	Thermal conductivity, λ _l [(W/m ²)/(K/m)]	S	S	S	S	S	S	(0.151)	(0.133)	(0.126)	V	V	V	V
	Boiling point: 34.4 °C	Dynamic viscosity, η _l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	S	(59)	35.5	29.4	V	V	V	V
	Critical temperature: 283.8 °C														
DIETHYL- SULFIDE	Chemical formula: C ₄ H ₁₀ S	Density, ρ _l (kg/m ³)	S	S	S	S	S	(954)	(905)	856	837	807	V	V	V
	Molecular weight: 90.18	Specific heat capacity, c _{p,l} (kJ/kg K)	S	S	S	S	S	(1.74)	1.767	1.847	1.889	1.899	V	V	V
	Melting point: -103.3 °C	Thermal conductivity, λ _l [(W/m ²)/(K/m)]	S	S	S	S	S	(0.176)	(0.160)	(0.142)	0.137	(0.126)	V	V	V
	Boiling point: 90.0 °C	Dynamic viscosity, η _l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	—	(104)	57.4	44.6	33.4	v	V	V
	Critical temperature: 283.8 °C														
THIOPHENE	Chemical formula: C ₄ H ₄ S	Density, ρ _l (kg/m ³)	S	S	S	S	S	S	S	1 086	1065	(1 013)	v	V	V
	Molecular weight: 84.14	Specific heat capacity, c _{p,l} (kJ/kg K)	S	S	S	S	S	S	S	1.43	1.46	(1.49)	v	V	V
	Melting point: -38.3 °C	Thermal conductivity, λ _l [(W/m ²)/(K/m)]	S	S	S	S	S	S	S	(0.142)	0.137	(0.128)	V	V	V
	Boiling point: 84.1 °C	Dynamic viscosity, η _l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	S	S	87.5	66.4	47.4	v	V	V
	Critical temperature: 297 °C														
THIOPHENE	Chemical formula: C ₄ H ₄ S	Density, ρ _l (kg/m ³)	S	S	S	S	S	S	S	1 086	1065	(1 013)	v	V	V
	Molecular weight: 84.14	Specific heat capacity, c _{p,l} (kJ/kg K)	S	S	S	S	S	S	S	1.43	1.46	(1.49)	v	V	V
	Melting point: -38.3 °C	Thermal conductivity, λ _l [(W/m ²)/(K/m)]	S	S	S	S	S	S	S	(0.142)	0.137	(0.128)	V	V	V
	Boiling point: 84.1 °C	Dynamic viscosity, η _l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	S	S	87.5	66.4	47.4	v	V	V
	Critical temperature: 297 °C														

INORGANIC SUBSTANCES

Substance	Data	Property	Temperature, °C												
			-200	-180	-160	-140	-120	-100	-50	0	20	50	100	150	200
			Temperature, K												
			73.15	93.15	113.15	133.15	153.15	173.15	223.15	273.15	293.15	323.15	373.15	423.15	473.15
HYDROGEN FLUORIDE	Chemical formula: HF	Density, ρ_l (kg/m ³)	S	S	S	S	S	S	1 123	1002	V	V	V	V	V
	Molecular weight: 20.01	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	S	S	2.97	3.60	V	V	V	V	V
	Melting point: -83.15 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	S	S	0.51	0.455	V	V	V	V	V
	Boiling point: 19.55 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	S	57	25.6	V	V	V	V	V
	Critical temperature: 187.85 °C														
HYDROGEN CHLORIDE	Chemical formula: HCl	Density, ρ_l (kg/m ³)	S	S	S	S	S	1 235	V	V	V	V	V	V	V
	Molecular weight: 36.46	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	S	1.60	v	V	V	V	V	V	V
	Melting point: -114.15 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	S	(0.421)	V	V	V	V	V	V	V
	Boiling point: -85.05 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	(58)	V	V	V	V	V	V	V
	Critical temperature: 51.45 °C														
HYDROGEN BROMIDE	Chemical formula: HBr	Density, ρ_l (kg/m ³)	S	S	S	S	S	S	2 132	V	V	V	V	V	V
	Molecular weight: 80.91	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	S	S	0.749	V	V	V	V	V	V
	Melting point: -86.9 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	S	S	0.131	V	V	V	V	V	V
	Boiling point: -67.05 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	S	(50)	V	V	V	V	V	V
	Critical temperature: 89.4 °C														
HYDROGEN IODIDE	Chemical formula: HI	Density, ρ_l (kg/m ³)	S	S	S	S	S	S	2 863	V	V	V	V	V	V
	Molecular weight: 127.91	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	S	S	0.460	V	V	V	V	V	V
	Melting point: -50.75 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	S	S	(0.173)	V	V	V	V	V	V
	Boiling point: -35.55 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	S	141.8	V	V	V	V	V	V
	Critical temperature: 150.85 °C														
HYDROGEN CYANIDE	Chemical formula: HCN	Density, ρ_l (kg/m ³)	S	S	S	S	S	S	S	715	688	V	V	V	V
	Molecular weight: 27.03	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	S	S	S	2.61	2.63	V	V	V	V
	Melting point: -14.2 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	S	S	S	(0.312)	(0.294)	V	V	V	V
	Boiling point: 25.7 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	S	S	23.55	19.2	V	V	V	V
	Critical temperature: 183.5 °C														
	Critical pressure: 5.39 MPa														

HYDROGEN SULFIDE	Chemical formula: H_2S	Density, ρ_l (kg/m ³)	S	S	S	S	S	S	980	V	V	V	V	V	V
	Molecular weight: 34.08	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	S	S	(1.875)	V	V	V	V	V	V
	Melting point: -8555° C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	S	S	(0.211)	V	V	V	V	V	V
	Boiling point: -60.35 °C Critical temperature: 100.05 °C Critical pressure: 89.4 MPa	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	S	(24)	V	V	V	V	V	V
AIR	Chemical formula:	Density, ρ_l (kg/m ³)	897	V	V	V	V	V	V	V	V	V	V	V	V
	Molecular weight: 28.96	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	1.957	V	V	V	V	V	V	V	V	V	V	V	V
	Melting point: -213 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	0.152	V	V	V	V	V	V	V	V	V	V	V	V
	Boiling point: -194.25 °C Critical temperature: -140.55 °C Critical pressure: 3.769 MPa	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	20.3	V	V	V	V	V	V	V	V	V	V	V	V
AMMONIA	Chemical formula: NH_3	Density, ρ_l (kg/m ³)	S	S	S	S	S	S	695	V	V	V	V	V	V
	Molecular weight: 17.03	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	S	S	4.45	V	V	V	V	V	V
	Melting point: -77.7 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	S	S	0.547	V	V	V	V	V	V
	Boiling point: -33.41 °C Critical temperature: 132.4 °C Critical pressure: 11.29MPa	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	S	31.7	V	V	V	V	V	V
NITROGEN DIOXIDE	Chemical formula: NO_2	Density, ρ_l (kg/m ³)	S	S	S	S	S	S	S	1 494	1446	V	V	V	V
	Molecular weight: 46.01	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	S	S	S	1.505	1.535	V	V	V	V
	Melting point: -11.25 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	S	S	S	0.140	0.130	V	V	V	V
	Boiling point: 2 1.15 °C Critical temperature: 158.25 °C Critical pressure: 1.013 MPa	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	S	S	49.4	4.21	V	V	V	V
CARBON MONOXIDE	Chemical formula: CO	Density, ρ_l (kg/m ³)	837	V	V	V	V	V	V	V	V	V	V	V	V
	Molecular weight: 28.01	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	2.16	V	V	V	V	V	V	V	V	V	V	V	V
	Melting point: -204.99 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	0.160	V	V	V	V	V	V	V	V	V	V	V	V
	Boiling point: -19 1.49 °C Critical temperature: -139.99 °C Critical pressure: 3.498 MPa	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	23.0	V	V	V	V	V	V	V	V	V	V	V	V
CARBON DIOXIDE	Chemical formula: CO_2	Density, ρ_l (kg/m ³)	S	S	S	S	S	S	1 154	V	V	V	V	V	V
	Molecular weight: 44.01	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	S	S	180	V	V	V	V	V	V
	Melting point: -56.55 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	S	S	(0.157)	V	V	V	V	V	V
	Boiling point: -78.45 °C Critical temperature: 31.05 °C Critical pressure: 72.95 MPa	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	S	15.5	V	V	V	V	V	V

INORGANIC SUBSTANCES (Continued)

Substance	Data	Property	Temperature, °C												
			-200	-180	-160	-140	-120	-100	-50	0	20	50	100	150	200
			Temperature, K												
			73.15	93.15	113.15	133.15	153.15	173.15	223.15	273.15	293.15	323.15	373.15	423.15	473.15
CARBONYL SULFIDE	Chemical formula: COS	Density, ρ_l (kg/m ³)	S	S	S	S	(1316)	1276	1 180	V	V	V	V	V	V
	Molecular weight: 60.07	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	1.20	1.19	1.22	V	V	V	V	V	V
	Melting point: -138.85 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	(0.274)	(0.251)	(0.199)	V	V	V	V	V	V
	Boiling point: -50.25 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	54.0	43.7	25.8	V	V	V	V	V	V
	Critical temperature: 102.2 °C														
CARBON DISULFIDE	Critical pressure: 6.5 MPa														
	Chemical formula: CS	Density, ρ_l (kg/m ³)	S	S	S	S	S	1 432	1 362	1 292	1 262	V	V	V	V
	Molecular weight: 76.13	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	S	0.988	0.988	0.996	1.00	V	V	V	V
	Melting point: -111.85 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	S	(0.212)	(0.194)	0.177	0.170	V	V	V	V
	Boiling point: 46.25 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	(138)	(68)	44.0	36.7	V	V	V	V
SULFUR DIOXIDE	Critical temperature: 278.85 °C														
	Critical pressure: 7.90 MPa														
	Chemical formula: SO	Density, ρ_l (kg/m ³)	S	S	S	S	S	S	1 557	V	V	V	V	V	V
	Molecular weight: 64.06	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	S	S	(1.381)	V	V	V	V	V	V
	Melting point: -74.45 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	S	S	0.242	V	V	V	V	V	V
PHOSGENE	Boiling point: -10.15 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	S	68.1	V	V	V	V	V	V
	Critical temperature: 157.65 °C														
	Critical pressure: 7.884 MPa														
	Chemical formula: COCl ₂	Density, ρ_l (kg/m ³)	S	S	S	S	(1715)	1 667	1 549	1436	V	V	V	V	V
	Molecular weight: 98.92	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	1.05	1.03	1.00	1.02	V	V	V	V	V
PHOSGENE	Melting point: -128.15 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	S	S	(0.150)	(0.138)	V	V	V	V	V
	Boiling point: 7.65 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	S	(220)	(114)	V	V	V	V	V
	Critical temperature: 181.85 °C														
	Critical pressure: 5.67 MPa														

ELEMENTS

			Temperature, °C												
			-200	-180	-160	-140	-120	-100	-50	0	20	50	100	150	200
			Temperature, K												
Substance	Data	Property	73.15	93.15	113.15	133.15	153.15	173.15	223.15	273.15	293.15	323.15	373.15	423.15	473.15
NITROGEN	Chemical formula: N ₂	Density, ρ_l (kg/m ³)	829	V	V	V	V	V	V	V	V	V	V	V	V
	Molecular weight: 28.01	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	1.99	V	V	V	V	V	V	V	V	V	V	V	V
	Melting point: -210 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	0.141	V	V	V	V	V	V	V	V	V	V	V	V
	Boiling point: —195.80 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	19.7	V	V	V	V	V	V	V	V	V	V	V	V
	Critical temperature: —146.9 °C														
	Critical pressure: 3.396 MPa														
OXYGEN	Chemical formula: O ₂	Density, ρ_l (kg/m ³)	1 226	V	V	V	V	V	V	V	V	V	V	V	V
	Molecular weight: 32.00	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	1.67	V	V	V	V	V	V	V	V	V	V	V	V
	Melting point: —218.8 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	0.179	V	V	V	V	V	V	V	V	V	V	V	V
	Boiling point: -182.97 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	31.4	V	V	V	V	V	V	V	V	V	V	V	V
	Critical temperature: —118.38 °C														
	Critical pressure: 5.05 MPa														
ARGON	Chemical formula: Ar	Density, ρ_l (kg/m ³)	S	1360	V	V	V	V	V	V	V	V	V	V	V
	Molecular weight: 39.95	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	1.13	V	V	V	V	V	V	V	V	V	V	V
	Melting point: —189.37 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	0.116	V	V	V	V	V	V	V	V	V	V	V
	Boiling point: —185.86 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	20.8	V	V	V	V	V	V	V	V	V	V	V
	Critical temperature: —122.29 °C														
	Critical pressure: 4.898 MPa														
FLUORINE	Chemical formula: F ₂	Density, ρ_l (kg/m ³)	1 140	V	V	V	V	V	V	V	V	V	V	V	V
	Molecular weight: 38.00	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	1.51	V	V	V	V	V	V	V	V	V	V	V	V
	Melting point: -220.15 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	(0.155)	V	V	V	V	V	V	V	V	V	V	V	V
	Boiling point: -187.95 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	34.9	V	V	V	V	V	V	V	V	V	V	V	V
	Critical temperature: —129.15 °C														
	Critical pressure: 5.32 MPa														

ELEMENTS (Continued)

			Temperature, °C												
			−200	−180	−160	−140	−120	−100	−50	0	20	50	100	150	200
			Temperature, K												
Substance	Data	Property	73.15	93.15	113.15	133.15	153.15	173.15	223.15	273.15	293.15	323.15	373.15	423.15	473.15
CHLORINE	Chemical formula: Cl*	Density, ρ_l (kg/m ³)	S	S	S	S	S	1 717	1 598	V	V	V	V	V	V
	Molecular weight: 70.91	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	S	0.883	0.892	V	V	V	V	V	V
	Melting point: −100.50 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	S	0.198	0.186	v	V	V	V	V	V
	Boiling point: −34.04 °C	Dynamic viscosity, η_l (10 ^{−5} Ns/m ²)	S	S	S	S	S	104.0	55.4	v	V	V	V	V	V
	Critical temperature: 144.0 °C														
BROMINE	Critical pressure: 7.7 1 MPa														
	Chemical formula: Br ₂	Density, ρ_l (kg/m ³)	S	S	S	S	S	S	S	3 208	3 140	(3040)	v	V	V
	Molecular weight: 159.81	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	S	S	S	0.448	0.452	0.456	V	V	V
	Melting point: −8.25 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	S	S	S	(0.129)	0.124	0.117	V	V	V
	Boiling point: 58.75 °C	Dynamic viscosity, η_l (10 ^{−5} Ns/m ²)	S	S	S	S	S	S	S	124	99.6	76.2	V	V	V
IODINE	Critical temperature: 310.85 °C														
	Critical pressure: 10.3 MPa														
	Chemical formula: I*	Density, ρ_l (kg/m ³)	S	S	S	S	S	S	S	S	S	S	S	3780	V
	Molecular weight: 253.81	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	S	S	S	S	S	S	S	0.318	V
	Melting point: 113.65 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	S	S	S	S	S	S	S	0.112	v
SULFUR	Boiling point: 184.35 °C	Dynamic viscosity, η_l (10 ^{−5} Ns/m ²)	S	S	S	S	S	S	S	S	S	S	S	179.8	V
	Critical temperature: 545.85 °C														
	Critical pressure: 11.65 MPa														
			Temperature, °C												
			−150	−100	−75	−50	−25	0	20	50	100	150	200	250	300
			Temperature, K												
			123.15	173.15	198.15	223.15	248.15	273.15	293.15	323.15	373.15	423.15	473.15	523.15	573.15
SULFUR	Chemical formula: S ₂	Density, ρ_l (kg/m ³)	S	S	S	S	S	S	S	S	S	1 780	1744	—	—
	Molecular weight: 64.12	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	S	S	S	S	S	0.570	0.570	0.570	0.570
	Melting point: 112.8 °C	Thermal conductivity, λ_l [(W/m ²)/(K/m)]	S	S	S	S	S	S	S	S	S	0.137	0.154	—	—
	Boiling point: 444.6 °C	Dynamic viscosity, η_l (10 ^{−5} Ns/m ²)	S	S	S	S	S	S	S	S	S	705	79.1	—	—
	Critical temperature: 1041 °C														
SULFUR	Critical pressure: 20.7 MPa														

MERCURY	Chemical formula: Hg	Density, ρ_l (kg/m ³)	S	S	S	S	(13660)	13595	13546	13473	13351	13231	13112	12993	12874
	Molecular weight: 200.51	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	(1.41)	0.1404	0.1396	0.1385	0.1371	0.1361	0.1355	0.1352	0.1353
	Melting point: -38.83 °C	Thermal conductivity, A, [(W/m ²)/(K/m)]	S	S	S	S	(7.85)	8.175	8.447	8.842	9.475	10.074	10.64	11.18	11.69
	Boiling point: 356.95 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	(190)	168.7	155.6	140.0	124.1	112.0	103.9	97.5	92.6
	Critical temperature: 1490.05 °C														
HEAT TRANSFER MEDIA															
Substance	Data	Property	Temperature, °C												
			-150	-100	-75	-50	-25	0	20	50	100	150	200	250	300
Substance	Data	Property	Temperature, K												
			123.15	173.15	198.15	223.15	248.15	273.15	293.15	323.15	373.15	423.15	473.15	523.15	573.15
DOWTHERM A	Chemical formula*	Density, ρ_l (kg/m ³)	S	S	S	S	S	S	1060	1 036	995	951	906	858	V
	Molecular weight: 166	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	S	S	S	1.574	1.660	1.800	1.947	2.087	2.219	V
	Melting point: 12 °C	Thermal conductivity, A, [(W/m ²)/(K/m)]	S	S	S	S	S	S	0.141	0.137	0.132	0.125	0.119	0.113	v
	Boiling point: 257.1 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	S	S	S	380	215	100	58	39	28	
	Critical temperature: 497 °C														
*Mixture (C ₆ H ₅) ₂ O (73.5 %);(C ₆ H ₅) ₂ (26.5%)															
DOWTHERM J	Chemical formula: C ₁₀ H ₁₄	Density, ρ_l (kg/m ³)	S	S	S	917	897	888	872	842	801	754	V	V	V
	Molecular weight: 134	Specific heat capacity, $c_{p,l}$ (kJ/kg K)	S	S	S	1.650	1.713	1.772	1.830	1.924	2.093	2.278	V	V	V
	Melting point: —	Thermal conductivity, A, [(W/m ²)/(K/m)]	S	S	S	0.137	0.135	0.134	0.133	0.130	0.126	0.122	V	V	V
	Boiling point: 181 °C	Dynamic viscosity, η_l (10 ⁻⁵ Ns/m ²)	S	S	S	410	225	140	90	62	36	22	V	V	V
	Critical temperature: 383 °C														
Critical pressure: 2.837 MPa															

HYDROGEN CYANIDE	Chemical formula: HCN													
	Molecular weight: 27.03													
	Normal density (at 0°C, 101.3 kPa): 1.21 kg/m³													
	Boiling point: 25.7°C													
	Critical temperature: 183.5°C													
	Critical pressure: 5.39 MPa													
HYDROGEN SULFIDE	Chemical formula: H ₂ S													
	Molecular weight: 34.08													
	Normal density (at 0°C, 101.3 kPa): 1.54 kg/m³													
	Boiling point: −60.35°C													
	Critical temperature: 100°C													
	Critical pressure: 8.937 MPa													
AMMONIA	Chemical formula: NH ₃													
	Molecular weight: 17.03													
	Normal density (at 0°C, 101.3 kPa): 0.77 kg/m³													
	Boiling point: −33.4°C													
	Critical temperature: 132.4°C													
	Critical pressure: 11.29 MPa													
NITRIC OXIDE	Chemical formula: NO													
	Molecular weight: 30.01													
	Normal density (at 0°C, 101.3 kPa): 1.34 kg/m³													
	Boiling point: −151.75°C													
	Critical temperature: −93.15°C													
	Critical pressure: 6.48 MPa													

Inorganic substances (continued)

Substance	Data	Property (at low pressure)	Temperature, °C												
			— 150	- 100	- 50	0	25	100	200	300	400	500	1 000	1500	2 000
Substance	Data	Property (at low pressure)	Temperature, K												
			123.15	173.15	223.15	273.15	298.15	373.15	473.15	573.15	673.15	773.15	1273.15	1773.15	2 273.15
NITROUS OXIDE	Chemical formula: N_2O Molecular weight: 44.01 Normal density (at 0°C, 101.3 kPa): 1.97 kg/m ³ Boiling point: -88.45°C Critical temperature: 36.43°C Critical pressure: 7.159 MPa	Specific heat capacity, $c_{p,g}$ (kJ/kg K)	S	S	0.816	0.858	0.879	0.950	1.017	1.076	1.130	1.176	1.285	1.331	1.361
		Thermal conductivity, λ_g [W/m ²]/(K/m)]	S	S	0.011	0.015	0.017	0.024	0.032	0.041	0.050	0.059	—	—	—
		Dynamic viscosity, η_g (10 ⁻⁵ Ns/m ²)	S	S	1.11	1.36	1.49	1.83	2.25	2.65	3.02	—	—	—	—
CARBON MONOXIDE	Chemical formula: CO Molecular weight: 28.01 Normal density (at 0°C, 101.3 kPa): 1.25 kg/m ³ Boiling point: -191.49°C Critical temperature: -139.99°C Critical pressure: 3.498 MPa	Specific heat capacity, $c_{p,g}$ (kJ/kg K)	—	1.038	1.038	1.038	1.038	1.038	1.055	1.080	1.105	1.130	1.235	1.285	1.315
		Thermal conductivity, λ_g [W/m ²]/(K/m)]	0.011	0.015	0.019	0.023	0.025	0.030	0.037	0.043	0.049	0.055	—	—	—
		Dynamic viscosity, η_g (10 ⁻⁵ Ns/m ²)	0.81	1.12	1.40	1.66	1.78	2.11	2.51	2.87	3.20	3.52	4.90	—	—
CARBON DIOXIDE	Chemical formula: CO ₂ Molecular weight: 44.01 Normal density (at 0°C, 101.3 kPa): 1.97 kg/m ³ Boiling point: -78.5°C Critical temperature: 31.04°C Critical pressure: 7.382 MPa	Specific heat capacity, $c_{p,g}$ (kJ/kg K)	S	S	0.775	0.816	0.846	0.934	1.001	1.063	1.114	1.156	1.269	1.319	1.352
		Thermal conductivity, λ_g [W/m ²]/(K/m)]	S	S	0.011	0.015	0.016	0.022	0.030	0.038	0.045	0.052	—	—	—
		Dynamic viscosity, η_g (10 ⁻⁵ Ns/m ²)	S	S	1.13	1.37	1.49	1.82	2.22	2.59	2.93	3.24	4.59	—	—
SULFUR DIOXIDE	Chemical formula: SO ₂ Molecular weight: 64.06 Normal density (at 0°C, 101.3 kPa): 2.92 kg/m ³ Boiling point: -10.15°C Critical temperature: 157.65°C Critical pressure: 7.884 MPa	Specific heat capacity, $c_{p,g}$ (kJ/kg K)	S	S	L	0.586	0.607	0.662	0.712	0.754	0.787	0.816	0.883	0.921	0.946
		Thermal conductivity, λ_g [W/m ²]/(K/m)]	S	S	L	0.0086	0.0099	0.014	0.019	0.024	0.029	0.034	—	—	—
		Dynamic viscosity, η_g (10 ⁻⁵ Ns/m ²)	S	S	L	1.17	1.28	1.63	2.07	2.46	2.80	3.15	—	—	—

5.5.12

Thermal and mechanical properties of heat exchanger construction material

Clive F. Beaton

■ This section provides data on the three essential properties of materials required for the design of heat exchangers, namely thermal conductivity, the mean coefficient of expansion (from ambient temperature to required temperature), and the modulus of elasticity. A wide variety of materials is used in practice, and the materials listed in the Standards of the American Society of Mechanical Engineers (ASME) have been taken as a basis for this report, with a few additions. The Unified Numbering System (UNS) and the Werkstoff-Nummer (WN) or DIN-Norm (DIN) have been given where applicable.

Different data sources give large variations (frequently up to 25%) in the values of these properties at high and/or low temperatures. In particular, significant disagreement between ASME and TEMA (Tubular Exchanger Manufacturers Association) tables is frequent. Where alternative sources have been referenced, preferred values have been adopted.

Data for many of the materials are available only at ambient temperatures, and values at other temperatures have been estimated by assuming the temperature variation to be similar for similar materials. Curves of property versus temperature sometimes exhibit maxima and minima, for example, in the thermal conductivity of some chromium steels or of aluminum alloys and in the coefficient of expansion of steels at high temperatures. In such cases it was not possible to extrapolate values from data over a limited temperature range because the point of inflection was unknown.

Values are given for carbon and low alloy steels (Table 1), high chrome steels (Table 2), nickel and nickel alloys (Table 3), copper and copper alloys (Table

4), aluminum alloys (Table 5), and titanium, zirconium, and cast iron (Table 6). Quantities and units used are: ρ , density (g/cm³); TC, thermal conductivity (W/m K); CE, coefficient of expansion (1/K), and ME, modulus of elasticity (GPa) (GPa = 10⁹ Pa; 1 Pa = 1 N/m²; 1 psi = 6.894 757 x 10³ Pa).

Tabular information is given for the following materials:

	UNS	WN*
Carbon steels		
Carbon/silicon		
Carbon/manganese		
Carbon/manganese/silicon		
C-1/2Mo; 1/2Cr-1/2Mo;		
1/2Cr-1/5Mo-V;		
1-3/4Cr-1/2Mo-Cu		1.5423
1/2Cr-1/4Mo-Si;		
1Cr-1/2Mo-V;		
1-1/4Cr-1/2Mo;		
1-1/4Cr-1/2Mo-Si		1.7335
1Cr-1/5Mo; 1Cr-1/2Mo		1.7335
2Cr-1/2Mo		—
1Cr-1/5Mo-Si		1.7335
2-1/4Cr-1Mo		1.7380
3Cr-1Mo		—
5Cr-1/2Mo		1.7362
5Cr-1/2Mo-Si		1.7362
5Cr-1/2Mo-Ti		—
7Cr-1/2Mo		1.7368
9Cr-1Mo		1.7386
1/2Ni-1/2Cr-1/4Mo-V		—

5.5.12-2 5.5 PHYSICAL PROPERTY DATA TABLES / 5.512 Properties of Heat Exchanger Construction Materials

	UNS	WN*		UNS	WN*
3/4Cr-1/2Ni-Cu		—	Nickle 400	NO4400	2.4360
3/4Cr-3/4Ni-Cu-Al		—	Nickel 405	NO4405	—
3/4Ni-1/2Cu-Mo		—	Nickel 600	NO6600	2.4816
1Ni-1/2Cr-1/2Mo		—	Nickel 800	NO8800	1.4876
1-3/4Ni-3/4Cr-1/4Mo		—	Nickel 825	NO8825	2.4858
2-1/2Ni		1.5635	Alloy X	NO6002	2.4606
3/4Ni-1/2Mo-1/3Cr-V		—	Alloy C4	NO6455	2.4610
1/2Ni-1/2Mo-V;			Alloy 625	NO6625	2.4856
3/4Ni-1/2Cr-1/2Mo-V;			Alloy G	NO6007	—
3/4Ni-1/2Mo-Cr-V;			Alloy G3	NO6985	2.4603
3/4Ni-1Mo-3/4Cr		—	Alloy B	N1001	2.4810
1/2Cr-1/2Ni-1/5Mo		—	Alloy B2	N10665	2.4617
2Ni-3/4Cr-1/3Mo		—	Alloy 276	N10276	2.4819
2Ni-3/4Cr-1/4Mo		—	Alloy C22	—	—
3-1/2Ni		1.5637	Copper and copper alloys		
3-1/2Ni-1-3/4Cr-1/2Mo-V		—	Copper	CI0200	2.0040
5Ni-1/4Mo		—	Muntz metal	C36500	2.0372
8Ni		—	Admiralty brass	C44300	2.0470
9Ni		1.5662	Naval brass	C46400	2.0530
Mn- 1/2Mo		—	Phosphor bronze A	C51000	2.1016
Mn- 1/2Mo-1/4Ni		—	Aluminum bronze D	C61400	2.0932
Mn-1/2Mo-1/2Ni		—	Aluminum brass	C68700	2.0460
Mn-1/2Mo-3/4Ni		1.6310	Copper nickel 90/10	C70600	2.0872
Mn- 1/4Mo		—	Copper nickel 80/20	C71000	2.0878
Mn-V		—	Copper nickel 70/30	C71500	2.0882
High chrome steels			Aluminum alloys (annealed condition)		
12Cr-1Al	S40500	1.4002	Alloy 1100	A91 100	3.0205
13Cr	S41000	1.4006	Alloy 3003	A93003	3.0517
15Cr	S42900	—	Alloy 5052	A95052	3.3523
17Cr	S43000	1.4016	Alloy 5083	A95083	3.3547
18Cr/8Ni	S30400	1.4301	Alloy 6061	A9606 1	3.3211
23Cr/12Ni	S30900	1.4828	Alloy 6063	A96063	3.3206
25Cr/20Ni	S31000	1.4841	Miscellaneous materials		
16Cr/12Ni/2Mo	S31600	1.4401	Unalloyed titanium		
18Cr/13Ni/3Mo	S31700	—	(grade 2)	R50400	3.7055
18Cr/10Ni/Ti	S32100	1.4541	Zirconium	—	—
18Cr/10Ni/Cb	S34700	1.4550	Grey cast iron	—	—
18Cr/ 18Ni/2Si	S38100	—			
Nickel and nickel alloys					
Nickel 200	NO2200	2.4066			
Nickel 201	NO2201	2.4068			

***Note:** Where no Werkstoff-Nummer is given, there is no equivalent to the **ASME** materials quoted.

5.513

Properties of seawater

Clive F. Beaton

■ Values of thermal conductivity, dynamic viscosity, heat capacity, density, and Prandtl number for seawater and its concentrates are *given*.

Table 1 Composition of seawater

	19.344
Sodium	10.773
Sulfate	2.712
Magnesium	1.294
Calcium	0.412
	0.399
Bicarbonate	1.142
Bromide	
Strontium	0.008
	0.004
Fluoride	

Table 1 gives the major components of seawater at its normal salinity of 35‰, though samples from different salinities range from 32–40‰.

Samples reported at other salinities may be considered merely as having more or less pure water, but at the highest concentrations reported some salts (notably calcium sulfates) will have exceeded their solubilities and precipitated from solutions.

Tables 2-9 appear on the following pages. References for these tables and equations representing the change in value with temperature and salinity can be found in Data Item Number 77024 published by the Engineering Sciences Data Unit, 251-259 Regent Street, London W1R 7AD.

S‰ Cl‰ (1)

(The symbol ‰ denotes parts per thousand of seawater.) Chlorinity and salinity are now more accurately found by measuring the ratio of the electrical conductivity of the unknown sample to that of a standard seawater sample.

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Table 2 Thermal conductivity of seawater and its concentrates (mW/m²)/(K/m)

<i>t</i> , °C	Salinity, g/kg																
	0 ^a	10	20	30	35 ^b	40	50	60	70	80	90	100	110	120	130	140	150
0	572	570	569	567	566	565	563	562	560	558	556	554	552	550	548	546	544
10	589	587	586	584	584	583	581	580	578	577	575	573	571	570	568	566	564
20	604	603	602	600	600	599	598	597	595	594	592	591	589	588	586	585	583
30	618	617	616	615	614	614	613	612	611	609	608	607	606	604	603	602	600
40	630	629	629	628	628	627	626	626	625	624	623	622	621	620	618	617	616
50	641	641	640	640	639	639	639	638	637	637	636	635	634	633	632	631	630
60	651	651	650	650	650	650	649	649	649	648	648	647	646	646	645	644	644
70	659	659	659	659	659	659	659	659	658	658	658	658	657	657	656	656	655
80	666	666	667	667	667	667	667	667	667	667	667	667	667	666	666	666	666
90	672	672	673	673	673	674	674	674	674	675	675	675	675	675	675	675	675
100	676	677	678	678	679	679	680	680	681	681	681	682	682	682	682	682	683
110	680	681	682	683	683	683	684	685	685	686	687	687	688	688	688	689	689
120	682	683	684	685	686	686	687	688	689	690	691	691	692	693	693	694	694
130	683	685	686	687	688	688	690	691	692	693	694	695	695	696	697	698	699
140	684	685	687	688	689	689	691	692	693	694	696	697	698	699	700	701	702
150	683	684	686	688	688	689	691	692	694	695	696	698	699	700	701	702	703
160	681	683	684	686	687	688	690	691	693	694	696	697	699	700	701	703	704
170	678	680	682	684	685	686	687	689	691	693	694	696	698	699	701	702	704
180	674	676	678	680	681	682	684	686	686	690	692	694	695	697	699	700	702

While these values for pure water are within the claimed accuracy, more accurate values are available in the appropriate ESDU Data Item.

^b“Normal” seawater.

Table 3 Dynamic viscosity of seawater and its concentrates (10^{-3} Ns/m²)

t , °C	Salinity, g/kg															
	0 ^a	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150
0	1.775	1.802	1.831	1.861	1.893	1.928	1.965	2.005	2.049	2.096	2.147	2.202	2.261	2.326	2.395	2.470
10	1.304	1.327	1.350	1.375	1.401	1.429	1.459	1.491	1.526	1.563	1.603	1.646	1.693	1.743	1.797	1.855
20	1.002	1.021	1.041	1.061	1.083	1.106	1.131	1.157	1.185	1.216	1.248	1.283	1.321	1.361	1.404	1.451
30	0.797	0.814	0.830	0.848	0.866	0.886	0.906	0.929	0.952	0.977	1.004	1.033	1.064	1.098	1.133	1.171
40	0.653	0.667	0.681	0.696	0.712	0.729	0.747	0.765	0.786	0.807	0.830	0.854	0.880	0.908	0.938	0.970
50	0.546	0.559	0.571	0.585	0.599	0.613	0.629	0.645	0.662	0.681	0.700	0.721	0.744	0.768	0.793	0.821
60	0.466	0.477	0.488	0.500	0.512	0.525	0.539	0.553	0.568	0.584	0.602	0.620	0.639	0.660	0.682	0.706
70	0.404	0.414	0.424	0.434	0.445	0.457	0.469	0.481	0.495	0.509	0.524	0.540	0.558	0.576	0.595	0.616
80	0.355	0.364	0.373	0.382	0.392	0.402	0.413	0.424	0.436	0.449	0.463	0.477	0.492	0.508	0.525	0.544
90	0.315	0.323	0.331	0.340	0.349	0.358	0.368	0.378	0.389	0.400	0.412	0.425	0.439	0.453	0.469	0.485
100	0.282	0.290	0.297	0.305	0.313	0.322	0.331	0.340	0.350	0.360	0.371	0.383	0.395	0.408	0.422	0.436
110	0.255	0.262	0.269	0.276	0.284	0.291	0.300	0.308	0.317	0.326	0.336	0.347	0.358	0.370	0.382	0.395
120	0.232	0.239	0.245	0.252	0.259	0.266	0.273	0.281	0.289	0.298	0.307	0.317	0.327	0.337	0.349	0.361
130	0.213	0.219	0.225	0.231	0.237	0.244	0.251	0.258	0.266	0.273	0.282	0.291	0.300	0.310	0.320	0.331
140	0.196	0.201	0.207	0.213	0.219	0.225	0.231	0.238	0.245	0.252	0.260	0.268	0.277	0.286	0.295	0.305
150	0.181	0.187	0.192	0.197	0.203	0.208	0.214	0.221	0.227	0.234	0.241	0.249	0.256	0.265	0.273	0.283
160	0.169	0.173	0.178	0.183	0.189	0.194	0.200	0.205	0.211	0.218	0.224	0.231	0.239	0.246	0.254	0.263
170	0.157	0.162	0.167	0.171	0.176	0.181	0.186	0.192	0.198	0.203	0.210	0.216	0.223	0.230	0.237	0.245
180	0.147	0.152	0.156	0.161	0.165	0.170	0.175	0.180	0.185	0.191	0.196	0.202	0.209	0.215	0.222	0.230

^aWhile these values for pure water are within the claimed accuracy, more accurate values are available in the appropriate ESDU Data Item.

Table 4 Dynamic viscosity of seawater (10^{-3} Ns/m²)

t , °C	Salinity, g/kg										
	30	31	32	33	34	35	36	37	38	39	40
0	1.861	1.864	1.867	1.871	1.874	1.877	1.880	1.883	1.887	1.890	1.893
10	1.375	1.377	1.380	1.382	1.365	1.388	1.390	1.393	1.396	1.398	1.401
20	1.061	1.063	1.065	1.068	1.070	1.072	1.074	1.076	1.078	1.081	1.083
30	0.848	0.850	0.851	0.853	0.855	0.857	0.859	0.861	0.862	0.864	0.866
40	0.696	0.698	0.699	0.701	0.702	0.704	0.706	0.707	0.709	0.710	0.712
50	0.585	0.586	0.587	0.589	0.590	0.592	0.593	0.594	0.596	0.597	0.599
60	0.500	0.501	0.503	0.504	0.505	0.506	0.507	0.509	0.510	0.511	0.512
70	0.434	0.435	0.437	0.438	0.439	0.440	0.441	0.442	0.443	0.444	0.445
80	0.382	0.383	0.384	0.385	0.386	0.387	0.388	0.389	0.390	0.391	0.392
90	0.340	0.341	0.342	0.343	0.343	0.344	0.345	0.346	0.347	0.348	0.349
100	0.305	0.306	0.307	0.308	0.308	0.309	0.310	0.311	0.312	0.312	0.313
110	0.276	0.277	0.278	0.278	0.279	0.280	0.281	0.281	0.282	0.283	0.284
120	0.252	0.252	0.253	0.254	0.254	0.255	0.256	0.257	0.257	0.258	0.259
130	0.231	0.231	0.232	0.233	0.233	0.234	0.235	0.235	0.236	0.237	0.237
140	0.213	0.213	0.214	0.215	0.215	0.216	0.216	0.217	0.218	0.218	0.219
150	0.197	0.198	0.198	0.199	0.199	0.200	0.200	0.201	0.202	0.202	0.203
160	0.183	0.184	0.184	0.185	0.186	0.186	0.187	0.187	0.188	0.188	0.189
170	0.171	0.172	0.172	0.173	0.173	0.174	0.174	0.175	0.175	0.176	0.176
180	0.161	0.161	0.161	0.162	0.162	0.163	0.163	0.164	0.164	0.165	0.165

Table 5 Heat capacity of seawater and its concentrates (kJ/kg K)

$t, ^\circ\text{C}$	Salinity, g/kg															
	0 ^a	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150
0	4.209	4.143	4.081	4.021	3.964	3.910	3.858	3.809	3.763	3.720	3.679	3.641	3.606	3.573	3.543	3.516
10	4.198	4.136	4.077	4.020	3.965	3.913	3.863	3.815	3.770	3.727	3.686	3.648	3.612	3.579	3.547	3.518
20	4.189	4.131	4.074	4.020	3.967	3.917	3.868	3.822	3.777	3.735	3.694	3.656	3.619	3.584	3.552	3.521
30	4.184	4.128	4.074	4.021	3.971	3.922	3.874	3.829	3.785	3.743	3.702	3.663	3.626	3.591	3.557	3.525
40	4.180	4.127	4.075	4.024	3.975	3.927	3.881	3.836	3.793	3.751	3.710	3.671	3.633	3.597	3.562	3.529
50	4.180	4.128	4.078	4.029	3.981	3.934	3.888	3.844	3.801	3.759	3.719	3.679	3.641	3.604	3.568	3.533
60	4.181	4.131	4.082	4.034	3.987	3.941	3.896	3.853	3.810	3.768	3.727	3.687	3.649	3.611	3.574	3.538
70	4.186	4.137	4.088	4.041	3.995	3.950	3.905	3.861	3.819	3.777	3.736	3.696	3.657	3.618	3.581	3.544
80	4.192	4.144	4.096	4.050	4.004	3.959	3.914	3.871	3.828	3.786	3.745	3.704	3.665	3.626	3.588	3.551
90	4.202	4.154	4.106	4.059	4.014	3.968	3.924	3.880	3.837	3.795	3.754	3.713	3.673	3.634	3.595	3.558
100	4.213	4.165	4.118	4.071	4.025	3.979	3.934	3.891	3.847	3.805	3.763	3.722	3.682	3.642	3.603	3.565
110	4.228	4.179	4.131	4.083	4.037	3.991	3.946	3.901	3.857	3.815	3.772	3.731	3.690	3.651	3.612	3.573
120	4.245	4.195	4.146	4.097	4.050	4.003	3.957	3.912	3.868	3.825	3.782	3.740	3.700	3.659	3.620	3.582
130	4.264	4.213	4.162	4.113	4.064	4.016	3.970	3.924	3.879	3.835	3.792	3.750	3.709	3.669	3.629	3.591
140	4.286	4.233	4.181	4.129	4.079	4.030	3.982	3.936	3.890	3.845	3.802	3.760	3.718	3.678	3.639	3.601
150	4.311	4.255	4.201	4.148	4.096	4.045	3.996	3.948	3.902	3.856	3.812	3.769	3.728	3.688	3.649	3.611
160	4.338	4.279	4.222	4.167	4.113	4.061	4.010	3.961	3.913	3.867	3.823	3.780	3.738	3.698	3.659	3.622
170	4.367	4.306	4.246	4.188	4.132	4.078	4.025	3.974	3.926	3.878	3.833	3.790	3.748	3.708	3.670	3.634
180	4.399	4.334	4.271	4.210	4.152	4.095	4.041	3.988	3.938	3.890	3.844	3.800	3.758	3.719	3.681	3.646

While these **values** for pure water are within the claimed accuracy, more accurate **values** are available in the appropriate ESDU Data Item.

Table 6 Heat capacity of seawater (kJ/kg K)

<i>t</i> , °C	Salinity, g/kg										
	30	31	32	33	34	35	36	37	38	39	40
0	4.021	4.015	4.010	4.004	3.998	3.992	3.987	3.981	3.975	3.970	3.964
10	4.020	4.014	4.009	4.003	3.998	3.992	3.987	3.981	3.976	3.971	3.965
20	4.020	4.015	4.009	4.004	3.999	3.993	3.988	3.983	3.978	3.973	3.967
30	4.021	4.016	4.011	4.006	4.001	3.996	3.991	3.986	3.981	3.976	3.971
40	4.024	4.019	4.014	4.009	4.004	4.000	3.995	3.990	3.985	3.980	3.975
50	4.029	4.024	4.019	4.014	4.009	4.004	4.000	3.995	3.990	3.985	3.981
60	4.034	4.029	4.025	4.020	4.015	4.011	4.006	4.001	3.997	3.992	3.987
70	4.041	4.037	4.032	4.027	4.023	4.018	4.013	4.009	4.004	4.000	3.995
80	4.050	4.045	4.040	4.036	4.031	4.027	4.022	4.017	4.013	4.008	4.004
90	4.059	4.055	4.050	4.046	4.041	4.036	4.032	4.027	4.023	4.018	4.014
100	4.071	4.066	4.061	4.057	4.052	4.048	4.043	4.038	4.034	4.029	4.025
110	4.083	4.079	4.074	4.069	4.065	4.060	4.055	4.051	4.046	4.041	4.037
120	4.097	4.092	4.088	4.083	4.078	4.073	4.069	4.064	4.059	4.054	4.050
130	4.113	4.108	4.103	4.098	4.093	4.088	4.083	4.078	4.074	4.069	4.064
140	4.129	4.124	4.119	4.114	4.109	4.104	4.099	4.094	4.089	4.084	4.079
150	4.148	4.142	4.137	4.132	4.127	4.121	4.116	4.111	4.106	4.101	4.096
160	4.167	4.162	4.156	4.151	4.145	4.140	4.135	4.129	4.124	4.119	4.113
170	4.188	4.182	4.177	4.171	4.165	4.160	4.154	4.149	4.143	4.137	4.132
180	4.120	4.204	4.198	4.192	4.187	4.181	4.175	4.169	4.163	4.157	4.152

Table 7 Density of seawater and its concentrates (kg/m³)

<i>t</i> , °C	Salinity, g/kg															
	0	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150
0	999.8	1008.1	1016.2	1024.2	1032.0	1039.8	1047.6	1055.5	1063.5	1071.6	1079.7	1088.0	1096.2	1104.4	1112.5	1120.4
10	999.7	1007.7	1015.5	1023.2	1030.2	1038.4	1046.0	1053.8	1061.6	1069.6	1077.6	1085.7	1093.9	1102.0	1110.1	1118.0
20	998.4	1005.8	1013.3	1020.8	1028.3	1035.9	1043.5	1051.2	1058.9	1066.7	1074.5	1082.4	1090.3	1098.2	1106.2	1114.2
30	995.4	1002.8	1010.2	1017.6	1025.1	1032.6	1040.2	1047.8	1055.4	1063.1	1070.8	1078.5	1086.3	1094.1	1102.0	1109.9
40	991.9	999.2	1006.6	1013.9	1021.4	1028.8	1036.3	1043.8	1051.4	1059.0	1066.6	1074.2	1081.9	1089.6	1097.4	1105.2
50	987.7	995.0	1002.3	1009.7	1017.1	1024.5	1031.9	1039.4	1046.9	1054.4	1062.0	1069.5	1077.1	1084.8	1092.4	1100.1
60	982.9	990.2	997.5	1004.9	1012.2	1019.6	1027.0	1034.5	1041.9	1049.4	1056.9	1064.4	1072.0	1079.5	1087.1	1094.8
70	977.6	984.9	992.2	999.5	1006.9	1014.3	1021.7	1029.1	1036.5	1043.9	1051.4	1058.9	1066.4	1074.0	1081.5	1089.1
80	971.7	979.0	986.4	993.7	1001.1	1008.4	1015.8	1023.2	1030.6	1038.1	1045.5	1053.0	1060.5	1068.0	1075.6	1083.1
90	965.3	972.7	980.0	987.4	994.7	1002.1	1009.5	1017.0	1024.4	1031.8	1039.3	1046.8	1054.3	1061.8	1069.3	1076.8
100	958.4	965.8	973.2	980.6	988.0	995.4	1002.8	1010.3	1017.7	1025.2	1032.7	1040.2	1047.7	1055.2	1062.7	1070.3
110	951.0	958.5	965.9	973.3	980.8	988.3	995.7	1003.2	1010.7	1018.2	1025.7	1033.2	1040.8	1048.3	1055.9	1063.4
120	943.2	950.7	958.2	965.7	973.2	980.7	988.2	995.8	1003.3	1010.9	1018.4	1026.0	1033.6	1041.2	1048.7	1056.3
130	934.8	942.4	950.0	957.6	965.2	972.8	980.4	988.0	995.6	1003.2	1010.8	1018.5	1026.1	1033.7	1041.3	1049.0
140	926.1	933.8	941.4	949.1	956.8	964.5	972.2	979.9	987.6	995.2	1002.9	1010.6	1018.3	1026.0	1033.7	1041.4
150	916.9	924.7	932.5	940.3	948.1	955.9	963.7	971.4	979.2	987.0	994.8	1002.5	1010.3	1018.0	1025.8	1033.6
160	907.3	915.2	923.2	931.1	939.0	946.9	954.8	962.7	970.6	978.5	986.3	994.2	1002.0	1009.9	1017.7	1025.5
170	897.3	905.4	913.5	921.6	929.6	937.7	945.7	953.7	961.7	969.7	977.6	985.6	993.5	1001.4	1009.3	1017.2
180	887.0	895.3	903.5	911.7	919.9	928.1	936.3	944.4	952.6	960.7	968.7	976.8	984.8	992.8	1000.8	1008.7

While these values for pure water are within the claimed accuracy, more accurate values are available in the appropriate ESDU Data Item.

Table 8 Density of seawater (kg/m³)

t, °C	Salinity, g/kg										
	30	31	32	33	34	35	36	37	38	39	40
0	1 024.2	1 024.9	1 025.7	1 026.5	1027.3	1 028.1	1 028.9	1029.6	1 030.4	1 031.2	1 032.0
10	1 023.2	1 023.9	1 024.7	1 025.4	1 026.2	1 027.0	1 027.7	1 028.5	1 029.3	1 030.0	1 030.8
20	1 020.8	1021.5	1 022.3	1 023.0	1 023.8	1 024.5	1 025.3	1 026.0	1026.8	1 027.5	1 028.3
30	1017.6	1 018.4	1 019.1	1 019.9	1 020.6	1 021.4	1022.1	1 022.9	1 023.6	1 024.4	1025.1
40	1013.9	1 014.7	1 015.4	1 016.2	1 016.9	1 017.7	1 018.4	1019.1	1 019.9	1 020.6	1021.4
50	1 009.7	1 010.4	1011.2	1011.9	1012.6	1013.4	1014.1	1 014.8	1015.6	1 016.3	1 017.1
60	1 004.9	1005.6	1 006.3	1007.1	1 007.8	1 008.6	1 009.3	1 010.0	1 010.8	1011.5	1 012.2
70	999.5	1 000.3	1001.0	1 001.7	1 002.5	1 003.2	1003.9	1 004.7	1 005.4	1 006.2	1 006.9
80	993.7	994.4	995.2	995.9	996.6	997.4	998.1	998.8	999.6	1 000.3	1001.1
90	987.4	988.1	988.8	989.6	990.3	991.1	991.8	992.5	993.3	994.0	994.7
100	980.6	981.3	982.1	982.8	983.5	984.3	985.0	985.8	986.5	987.2	988.0
110	973.3	974.1	974.8	975.6	976.3	977.1	977.8	978.6	979.3	980.0	980.8
120	965.7	966.4	967.2	967.9	968.7	969.4	970.2	970.9	971.7	972.4	973.2
130	957.6	958.4	959.1	959.9	960.6	961.4	962.1	962.9	963.7	964.4	965.2
140	949.1	949.9	950.7	951.4	952.2	953.0	953.7	954.5	955.3	956.0	956.8
150	940.3	941.1	941.8	942.6	943.4	944.2	945.0	945.7	946.5	947.3	948.1
160	931.1	931.9	932.7	933.5	934.3	935.1	935.8	936.6	937.4	938.2	939.0
170	921.6	922.4	923.2	924.0	924.8	925.6	926.4	927.2	928.0	928.8	929.6
180	911.7	912.6	913.4	914.2	915.0	915.8	916.7	917.5	918.3	919.1	919.9

Table 9 Prandtl number of seawater and its concentrates

t_f °C	Salinity, g/kg																
	0 ^a	10	20	30	35 ^b	40	50	60	70	80	90	100	110	120	130	140	150
0	13.1	13.1	13.1	13.2	13.2	13.3	13.4	13.5	13.6	13.8	14.0	14.3	14.5	14.8	15.2	15.5	16.0
10	9.29	9.35	9.39	9.46	9.49	9.53	9.62	9.72	9.84	9.97	10.1	10.3	10.5	10.7	11.0	11.2	11.6
20	6.95	6.99	7.04	7.11	7.13	7.17	7.24	7.33	7.43	7.53	7.67	7.80	7.96	8.13	8.32	8.52	8.76
30	5.40	5.45	5.49	5.54	5.58	5.60	5.67	5.74	5.82	5.92	6.01	6.12	6.24	6.39	6.54	6.69	6.88
40	4.33	4.38	4.41	4.46	4.48	4.51	4.57	4.63	4.70	4.78	4.86	4.95	5.05	5.16	5.28	5.42	5.56
50	3.56	3.60	3.64	3.68	3.71	3.73	3.77	3.83	3.89	3.95	4.02	4.10	4.18	4.28	4.38	4.48	4.60
60	2.99	3.03	3.06	3.10	3.12	3.14	3.19	3.24	3.28	3.34	3.40	3.47	3.54	3.61	3.69	3.78	3.88
70	2.57	2.60	2.63	2.66	2.68	2.70	2.74	2.78	2.82	2.87	2.92	2.98	3.04	3.11	3.18	3.25	3.33
80	2.23	2.26	2.29	2.32	2.34	2.35	2.39	2.42	2.46	2.50	2.55	2.60	2.65	2.71	2.77	2.83	2.90
90	1.97	2.00	2.02	2.05	2.06	2.08	2.11	2.14	2.18	2.21	2.25	2.29	2.34	2.39	2.44	2.50	2.56
100	1.75	1.78	1.80	1.83	1.84	1.86	1.88	1.92	1.94	1.98	2.01	2.05	2.09	2.13	2.18	2.23	2.28
110	1.59	1.61	1.63	1.65	1.66	1.68	1.70	1.73	1.75	1.78	1.81	1.84	1.88	1.92	1.96	2.00	2.05
120	1.44	1.47	1.49	1.51	1.51	1.53	1.55	1.57	1.60	1.62	1.65	1.68	1.71	1.75	1.78	1.82	1.86
130	1.33	1.35	1.37	1.38	1.39	1.40	1.42	1.44	1.46	1.49	1.51	1.54	1.57	1.60	1.63	1.66	1.70
140	1.23	1.24	1.26	1.28	1.29	1.30	1.31	1.33	1.35	1.37	1.39	1.42	1.44	1.47	1.50	1.53	1.56
150	1.14	1.16	1.18	1.19	1.20	1.21	1.22	1.24	1.26	1.27	1.30	1.32	1.34	1.36	1.39	1.42	1.45
160	1.08	1.08	1.10	1.11	1.12	1.13	1.14	1.16	1.17	1.19	1.21	1.23	1.25	1.28	1.30	1.32	1.35
170	1.01	1.03	1.04	1.05	1.06	1.06	1.07	1.09	1.10	1.12	1.13	1.16	1.17	1.20	1.22	1.24	1.26
180	0.959	0.975	0.983	0.997	1.00	1.00	1.02	1.03	1.04	1.06	1.07	1.09	1.10	1.13	1.14	1.17	1.19

While these values for pure water are within the claimed accuracy, more accurate values are available in the appropriate ESDU Data Item.

^b "Normal" seawater.

HEDH

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