

CO₂ corrosion rate calculation model

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Foreword

The NORSOK standards are developed by the Norwegian petroleum industry to ensure adequate safety, value adding and cost effectiveness for petroleum industry developments and operations. Furthermore, NORSOK standards are as far as possible intended to replace oil company specifications and serve as references in the authorities' regulations.

The NORSOK standards are normally based on recognised international standards, adding the provisions deemed necessary to fill the broad needs of the Norwegian petroleum industry. Where relevant, NORSOK standards will be used to provide the Norwegian industry input to the international standardisation process. Subject to development and publication of international standards, the relevant NORSOK standard will be withdrawn.

The NORSOK standards are developed according to the consensus principle generally applicable for most standards work and according to established procedures defined in NORSOK A-001.

The NORSOK standards are prepared and published with support by The Norwegian Oil Industry Association (OLF) and Federation of Norwegian Manufacturing Industries (TBL).

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Introduction

This NORSOK standard, which is a recommended practice, contains

- a computer program for corrosion rate calculations which is available for downloading free of charge from the NORSOK internet website (<http://www.standard.no>) or can be procured from Standards Norway,
- a user manual for the computer program. A description of the calculation model, the algorithms and the conditions for the corrosion rate calculations are given. In additions, methods and algorithms for calculation of essential input parameters to the corrosion rate calculations are given.

1 Scope

This NORSOK standard presents a recommended practice for calculation of corrosion rates in hydrocarbon production and process systems where the corrosive agent is CO₂.

2 Normative and informative references

The following standards include provisions and guidelines which, through reference in this text, constitute provisions and guidelines of this NORSOK standard. Latest issue of the references shall be used unless otherwise agreed. Other recognized standards may be used provided it can be shown that they meet or exceed the requirements and guidelines of the standards referenced below.

2.1 Normative references

NORSOK M-001, Materials selection

2.2 Informative references

None

3 Terms, definitions and symbols

For the purposes of this NORSOK standard, the following terms, definitions and symbols apply.

3.1 Terms and definitions

3.1.1

can

verbal form used for statements of possibility and capability, whether material, physical or casual

3.1.2

may

verbal form used to indicate a course of action permissible within the limits of this NORSOK standard

3.1.3

shall

verbal form used to indicate requirements strictly to be followed in order to conform to this NORSOK standard and from which no deviation is permitted, unless accepted by all involved parties

3.1.4

should

verbal form used to indicate that among several possibilities one is recommended as particularly suitable, without mentioning or excluding others, or that a certain course of action is preferred but not necessarily required

3.2 Symbols

A	is the cross sectional area in m ²
$B_{(index)}$	is the constant used in viscosity calculations
$C_{(index)}$	is the concentration of component
CR _t	is the corrosion rate at temperature t in mm/year
D	is the pipe diameter in mm
F _{H₂O}	is the water mass flow in humidity calculations
F _{tot}	is the total mass flow in humidity calculations
$K_{(index)}$	is the equilibrium constant used in pH calculations
K _{SP}	is the equilibrium constant of iron carbonate
K _t	is the constant for the temperature t used in corrosion rate calculations
P	is the total system pressure in bar
Q _G	is the volumetric flow of gas in MSm ³ /d
Q _L	is the volumetric flow of liquid (i.e. liquid hydrocarbons and water) in Sm ³ /d
R	is μ_w/μ_o

Re	is the Reynolds number
S	is the wall shear stress in Pa
T	is the temperature given in Kelvin.
T_c	is the temperature given in °C
T_f	is the temperature given in °F
T_{std}	is the temperature given in Kelvin at standard conditions (60 °F/15,55 °C)
Z	is the compressibility of the gas
a	is the fugacity coefficient
f	is the friction factor
f_{CO_2}	is the fugacity of CO ₂ in bar
$f(pH)_t$	is the the pH factor at temperature t
k	is the pipe roughness in m
I	is the ionic strength given in molar
p_{CO_2}	is the CO ₂ partial pressure in bar
p_{H_2O}	is the H ₂ O vapour pressure in bar
t	is the 20 °C, 40 °C, 60 °C, 80 °C, 90 °C, 120 °C or 150 °C
u_G^S	is the superficial velocities of gas in m/s
u_L^S	is the superficial velocities of liquid in m/s
u_m	is the mixed velocity (m/s)
λ	is the liquid fraction
μ_o	is the viscosity of oil in Ns/m ²
μ_G	is the viscosity of gas in Ns/m ²
μ_L	is the viscosity of liquid in Ns/m ²
μ_m	is the mixed viscosity in Ns/m ²
μ_{relmax}	is the maximum relative viscosity (relative to the oil)
μ_w	is the viscosity of water in Ns/m ²
ρ_G	is the gas density in kg/m ³
ρ_L	is the liquid density in kg/m ³
ρ_m	is the mixed density in kg/m ³
ρ_o	is the oil density in kg/m ³
ρ_w	is the water density kg/m ³
ϕ	is the watercut
ϕ_c	is the watercut at inversion point

4 Principles for use of the computer program

The corrosion rate equations included in this NORSOK standard describe the calculation model which shall apply, while the computer program itself is an optional aid which the users of the model may apply such that they possess an efficient tool to conduct corrosion rate calculations and parameter studies. This computer program is developed based on the corrosion rate model given as equations in this NORSOK standard.

The computer program is an aid in CO₂ corrosion rate assessments, but the user of the computer program is responsible for the results and the final material selections and piping and equipment design. Therefore the user of the program shall perform a critical evaluation of all results and the applicability of these in each case. Corrosion rate calculation, is only one element in a material selection process. Other essential factors are uncertainty in input data for corrosion rate calculations, construction and commissioning conditions, consideration of normal and upset operating conditions, actual corrosivity of produced fluids, scale, wax, inhibitor efficiency and geometry of corrosion attacks. These and other factors may influence the actual corrosion rates considerably, and be more important than any uncertainty in the corrosion rate calculations.

As the computer program is distributed electronically and may be used on different computers and computer program versions, users of the computer program are sole responsible to verify that the computer calculations are in accordance with the equations in this NORSOK standard.

This NORSOK standard provides an introduction to the corrosion rate computer program. It also gives limitations and requirements to input parameters and results. Instructions for running the program are given in the help functions to the program.

The program covers only calculation of corrosion rates where CO₂ is the corrosive agent. It does not include additional effects of other constituents which may influence the corrosivity, e.g. contaminations of O₂, H₂S etc. If such constituents are present, which is common in e.g. produced water systems, these effects shall be evaluated separately.

Principles for materials selection are given in NORSOK M-001. The requirements in NORSOK M-001 shall be used when generating input data and when interpreting results from this NORSOK standard. It is important to note that this NORSOK standard and computer program may use or generate data which are outside the limits of NORSOK M-001. One example is corrosion inhibitor efficiency, where NORSOK M-001 provides maximum allowable values, while the computer program accepts all values from 0 % to 100 %. In case of conflict, NORSOK M-001 shall apply when selecting materials.

5 Description of the CO₂ corrosion rate model

5.1 General

The model is an empirical corrosion rate model for carbon steel in water containing CO₂ at different temperatures, pHs, CO₂ fugacities and wall shear stresses. It is based on flow-loop experiments at temperatures from 5 °C to 160 °C. A large amount of data at various temperatures, CO₂ fugacities, pHs and wall shear stresses are used.

The main bulk of the flow loop tests used in developing the calculation model is taken from research programs at Institute for Energy Technology (IFE) in Norway. The main principles for the testing is described in a paper by Dugstad et. al. /1/. Most of the data directly used in the modelling work has been generated after this paper /1/ was presented.

5.2 The corrosion model

The following general equation of the CO₂ corrosion rate for carbon steel at each of the temperatures (t); 20 °C, 40 °C, 60 °C, 80 °C, 90 °C, 120 °C and 150 °C is used:

$$CR_t = K_t \times f_{CO_2}^{0,62} \times (S/19)^{0,146 + 0,0324 \log(f_{CO_2})} \times f(pH)_t \quad (\text{mm/year}) \quad (1)$$

The following equation is used at temperature 15 °C:

$$CR_t = K_t \times f_{CO_2}^{0,36} \times (S/19)^{0,146 + 0,0324 \log(f_{CO_2})} \times f(pH)_t \quad (\text{mm/year}) \quad (2)$$

The following equation is used at temperature 5 °C:

$$CR_t = K_t \times f_{CO_2}^{0,36} \times f(pH)_t \quad (\text{mm/year}) \quad (3)$$

The corrosion rate between temperatures where a constant K_t has been generated, is found by a linear extrapolation between the calculated corrosion rate at the temperature above and below the desired temperature. The constant K_t is given in Table 1.

Table 1 - Constant K_t

Temperature °C	K_t
5	0,42
15	1,59
20	4,762
40	8,927
60	10,695
80	9,949
90	6,250
120	7,770
150	5,203

The effect of pH is given in Table 2.

Table 2 - pH function

Temperature °C	pH	f(pH)
5 5	$3,5 \leq \text{pH} < 4,6$ $4,6 \leq \text{pH} \leq 6,5$	$f(\text{pH}) = 2,0676 - (0,2309 \times \text{pH})$ $f(\text{pH}) = 4,342 - (1,051 \times \text{pH}) + (0,0708 \times \text{pH}^2)$
15 15	$3,5 \leq \text{pH} < 4,6$ $4,6 \leq \text{pH} \leq 6,5$	$f(\text{pH}) = 2,0676 - (0,2309 \times \text{pH})$ $f(\text{pH}) = 4,986 - (1,191 \times \text{pH}) + (0,0708 \times \text{pH}^2)$
20 20	$3,5 \leq \text{pH} < 4,6$ $4,6 \leq \text{pH} \leq 6,5$	$f(\text{pH}) = 2,0676 - (0,2309 \times \text{pH})$ $f(\text{pH}) = 5,1885 - (1,2353 \times \text{pH}) + (0,0708 \times \text{pH}^2)$
40 40	$3,5 \leq \text{pH} < 4,6$ $4,6 \leq \text{pH} \leq 6,5$	$f(\text{pH}) = 2,0676 - (0,2309 \times \text{pH})$ $f(\text{pH}) = 5,1885 - (1,2353 \times \text{pH}) + (0,0708 \times \text{pH}^2)$
60 60	$3,5 \leq \text{pH} < 4,6$ $4,6 \leq \text{pH} \leq 6,5$	$f(\text{pH}) = 1,836 - (0,1818 \times \text{pH})$ $f(\text{pH}) = 15,444 - (6,1291 \times \text{pH}) + (0,8204 \times \text{pH}^2) - (0,0371 \times \text{pH}^3)$
80 80	$3,5 \leq \text{pH} < 4,6$ $4,6 \leq \text{pH} \leq 6,5$	$f(\text{pH}) = 2,6727 - (0,3636 \times \text{pH})$ $f(\text{pH}) = 331,68 \times e^{(-1,2618 \times \text{pH})}$
90 90 90	$3,5 \leq \text{pH} < 4,57$ $4,57 \leq \text{pH} < 5,62$ $5,62 \leq \text{pH} \leq 6,5$	$f(\text{pH}) = 3,1355 - (0,4673 \times \text{pH})$ $f(\text{pH}) = 21254 \times e^{(-2,1811 \times \text{pH})}$ $f(\text{pH}) = 0,4014 - (0,0538 \times \text{pH})$
120 120 120	$3,5 \leq \text{pH} < 4,3$ $4,3 \leq \text{pH} < 5$ $5 \leq \text{pH} \leq 6,5$	$f(\text{pH}) = 1,5375 - (0,125 \times \text{pH})$ $f(\text{pH}) = 5,9757 - (1,157 \times \text{pH})$ $f(\text{pH}) = 0,546125 - (0,071225 \times \text{pH})$
150 150 150	$3,5 \leq \text{pH} < 3,8$ $3,8 \leq \text{pH} < 5$ $5 \leq \text{pH} \leq 6,5$	$f(\text{pH}) = 1$ $f(\text{pH}) = 17,634 - (7,0945 \times \text{pH}) + (0,715 \times \text{pH}^2)$ $f(\text{pH}) = 0,037$

5.3 The effect of glycol and corrosion inhibitors

The effect of glycol on the corrosion rate is calculated as a reduction factor, see /2/, as follows:

- glycol reduction factor = $10^{1,6 (\log (100 - \text{wt\%Glycol}) - 2)}$ for less than 95 weight % glycol;
- for > 95 weight % glycol, the glycol reduction factor is set to 0,008.

The effect of corrosion inhibitors is entered directly as a reduction factor in the computer program.

When both addition of corrosion inhibitors and glycol is entered into the computer program, the one effect giving the greatest corrosion rate reduction factor will be used for calculation of the resulting corrosion rate, i.e. the two effects will not be combined.

6 Structure of the computer programme

The computer program has a main dialogue box, denoted as the "Main Menu", where all corrosion rate calculations can be performed. All input parameters can be entered into the program directly at this stage for point calculations.

As options and support functions, it is possible to calculate several of the important parameters by selecting optional dialogue boxes. Such options are

- pH calculations,
- shear stress calculations,

- humidity calculations for gas systems (not an input parameter used in the calculations, but essential in evaluating risk for corrosion in gas systems).

These program options are included in order to generate adequate input data for corrosion rate prediction based on data normally presented in process flow diagrams and design basis documents. The support program options are prepared to give adequate accuracy for corrosion rate calculations, and shall not be used for other purposes, e.g. genuine process, scale or flow calculations.

In the clauses below, the input parameters and the corrosion rate calculation model are explained. Additionally, the support functions for calculation of some of the input parameters are explained.

Other support functions, such as "Parameter study", "Accumulated corrosion", saving of data, print of data etc. are not specifically explained in this NORSOK standard, but are covered by the "Help" function provided in the computer program.

7 Input parameters

7.1 Basic input parameters

The basic input parameters for the CO₂ corrosion model for carbon steel are given in Table 3. The allowed units and ranges are also given.

Table 3 - Basic input parameters

Parameter	Units	Range	Comments
Temperature	°C °F	5 to 150 68 to 302	
Total pressure	bar psi	1 to 1000 14,5 to 14500	
Total mass flow	kmole/h	10 ⁻³ to 10 ⁶	Only relevant when CO ₂ is given in kmole/h.
CO ₂ fugacity in the gas phase	bar psi mole% kmole/h	0,1 to 10 1,45 to 145 variable variable	The CO ₂ partial pressure shall be ≤ the total pressure. The allowed ranges of mole% and kmole/h CO ₂ are dependent on the total pressure.
Wall shear stress	Pa	1 to 150	Can be calculated by use of other input parameters, see 7.2.1.
PH		3,5 to 6,5	Can be calculated by use of other input parameters, see 7.2.2.
Glycol concentration	weight%	0 to 100	
Inhibitor efficiency	%	0 to 100	See NORSOK M-001

7.2 Other input parameters

7.2.1 Input parameters for wall shear stress calculations

To calculate the wall shear stress, the input parameters given in Table 4, are as a minimum required.

Table 4 - Input parameters for simplified calculation of wall shear stress

Parameter	Units	Range	Comments
Temperature	°C °F	5 to 150 41 to 302	
Total pressure	bar psi	1 to 1000 14,5 to 14500	
Superficial liquid velocity/ Liquid flow	m/s Sm ³ /d	0 to 20 (depends on internal pipe diameter)	Requirement: turbulent flow, i.e. Re > 2300
Superficial gas velocity/ Gas flow	m/s MSm ³ /d	0 to 40 (depends on internal pipe diameter)	Requirement: turbulent flow, i.e. Re > 2300
Watercut, ϕ	%	0 to 100	
Internal pipe diameter	mm	All diameters	Requirement: turbulent flow, i.e. Re > 2300

For more accurate wall shear stress calculations, the input parameters given in Table 5 should also be used.

Table 5 - Input parameters for accurate calculation of wall shear stress

Parameter	Units	Range	Default value
Roughness	μm	0 to 100	50
Compressibility		0,8 to 1	0,9
Specific gravity of gas relative to air		0,5 to 1	0,8
Water density, ρ_w	kg/m ³	995 to 1050	1024
Oil density, ρ_o	kg/m ³	600 to 1100	850
Gas density, ρ_g	kg/m ³	1 to 1700	calculated
Water viscosity, μ_w	cp N s/m ²	0,17 to 1,1 0,00017 to 0,0011	calculated
Oil viscosity, μ_o	cp N s/m ²	0,2 to 200 0,0002 to 0,2	1,1
Gas viscosity, μ_g	cp N s/m ²	0,02 to 0,06 0,00002 to 0,00006	0,03
Watercut at inversion point, ϕ_c		0,3 to 0,9	0,5
Maximum relative liquid viscosity, μ_{relmax}		1 to 100	7,06

7.2.2 Input parameters for pH calculations

To predict the pH in the condensed water or formation water, the parameters given in Table 6 are needed.

Table 6 - Input parameters for pH calculations

Parameter	Unit	Range	Default values	Comments
Temperature	°C °F	5 to 150 41 to 302		
Total pressure	bar psi	1 to 1000 14,5 to 14500		
Total mass flow	kmole/h	10 ⁻³ to 10 ⁶		Only relevant when CO ₂ is given in kmole/h.
CO ₂ fugacity	bar psi mole% kmole/h	0 to 10 0 to 145 variable variable		The CO ₂ partial pressure shall be < the total pressure. The allowed ranges of mole% and kmole/h CO ₂ are dependent on the total pressure.
Bicarbonate (HCO ₃ ⁻)	mg/l mM	0 to 20000 0 to 327	0	Default values for formation water.
Ionic strength/salinity	g/l M	0 to 175 0 to 3	50	Default values for formation water.

7.2.3 Humidity calculations

Table 7 - Input parameters for humidity calculation

Parameter	Unit	Range	Comments
Temperature	°C °F	-16 to 200 3,2 to 392	
Total pressure	bar psi	1 to 1000 14,5 to 14500	
Water mass flow	kmole/h	10 ⁻³ to 10 ⁶	
Total mass flow	kmole/h	10 ⁻³ to 10 ⁶	The water mass flow shall be ≤ the total mass flow.

8 Prediction of some of the input parameters

8.1 Fugacity of CO₂

Gases are not ideal at high pressures. To compensate for this, the partial pressure of a gas is multiplied by a fugacity constant. The real CO₂ pressure can then be expressed as:

$$f_{\text{CO}_2} = a \times p_{\text{CO}_2} \quad (4)$$

The CO₂ partial pressure is found by one of the following expressions:

$$p_{\text{CO}_2} = (\text{mole\% CO}_2 \text{ in the gas phase} / 100 \%) \times P \quad (5)$$

or

$$p_{\text{CO}_2} = \frac{\text{mass flow of CO}_2 \text{ in the gas phase (kmole/h)}}{\text{total mass flow in the gas phase (kmole/h)}} \times P \quad (6)$$

The fugacity coefficient is given as (see /2/):

$$a = 10^{P \times (0,0031 - 1,4/T)} \quad \text{for } P \leq 250 \text{ bar} \quad (7)$$

$$a = 10^{250 \times (0,0031 - 1,4/T)} \quad \text{for } P > 250 \text{ bar} \quad (8)$$

The total pressure is set to 250 bar in the fugacity constant for all pressures above 250 bar.

8.2 pH

8.2.1 General considerations

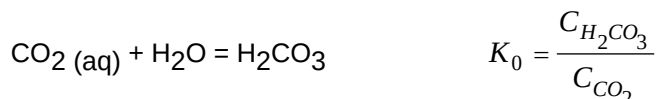
The program contains a pH calculation module. The pH in both condensed water and formation water can be calculated. Some essential general considerations relevant for pH assessment is given below.

The reported pH in water analyses is usually measured after depressurisation and atmospheric exposure of the sample. Such pHs give no information about the in situ pH which is a requisite for the corrosion rate evaluation. The in situ pH has to be determined by calculations which take into account the three controlling buffer systems $\text{CO}_2/\text{HCO}_3^-$, $\text{H}_2\text{S}/\text{HS}^-$ and $\text{CH}_3\text{COOH}/\text{CH}_3\text{COO}^-$. The buffer system $\text{CH}_3\text{COOH}/\text{CH}_3\text{COO}^-$ can be extended to include all the other organic acids that may influence the pH determination as these acids have similar dissociation constants.

The bicarbonate concentration, which is used for pH calculation, is routinely determined by titration and the reported value is set equal to the alkalinity. This is correct as long as the H_2S concentration is low and the system does not contain acetic acid. For waters containing significant amount of organic acids, the reported bicarbonate concentration requires correction because organic acids contributes to the measured value of total alkalinity. The correction will be 2/3 of the organic acid concentration assuming that the end point pH of the titration is 4.3. Lower pH requires a higher fraction. More details about the interpretation of the water analysis and the determination of pH can be found in the European Federation of Corrosion (EFC) publication number 16 /3/.

8.2.2 Calculation of pH

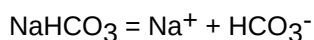
The routine for calculation of pH is based on the following chemical reactions and equilibrium constants:



The system has to be electro-neutral, which can be described by the following equation:

$$C_{\text{Na}^+} + C_{\text{H}^+} = C_{\text{HCO}_3^-} + 2C_{\text{CO}_3^{2-}} + C_{\text{OH}^-} + C_{\text{Cl}^-} \quad (9)$$

It is assumed that bicarbonate is added as sodium bicarbonate (NaHCO_3). It is also assumed that no other salts than sodium bicarbonate and sodium chloride (NaCl) are present in the solution. These salts will dissolve as follows:



Based on these assumptions, the amount of sodium bicarbonate equals the difference in the concentrations of sodium and chloride as shown below. The mass balance for bicarbonate will therefore be as follows:

$$C_{0,\text{Bicarb}} = C_{\text{Na}^+} - C_{\text{Cl}^-} \quad (10)$$

$C_{0,\text{Bicarb}}$ equals the initial amount of sodium bicarbonate.

By combining the equations for the equilibrium constants with the required electro-neutrality and the mass balance for bicarbonate one get the following expression for the concentration of the hydrogen cation:

$$C_{\text{H}^+}^3 + C_{0,\text{Bicarb}} C_{\text{H}^+}^2 - (K_H K_0 K_1 p_{\text{CO}_2} + K_W) \times C_{\text{H}^+} - 2K_H K_0 K_1 K_2 p_{\text{CO}_2} = 0 \quad (11)$$

This equation is solved by using the Newton's method.

The pH in a condensed water system saturated with iron carbonate can also be calculated. Based on a similar deduction as above, the equation becomes:

$$\left(\frac{2K_{\text{SP}}}{K_H K_0 K_1 K_2 p_{\text{CO}_2}} \right) C_{\text{H}^+}^4 + C_{\text{H}^+}^3 + C_{0,\text{Bicarb}} \times C_{\text{H}^+}^2 - (K_H K_0 K_1 p_{\text{CO}_2} + K_W) \times C_{\text{H}^+} - 2K_H K_0 K_1 K_2 p_{\text{CO}_2} = 0 \quad (12)$$

8.2.3 Equilibrium constants

The equilibrium constant and the forward reaction rate constant for the carbon dioxide hydration were given by Palmer and van Eldik /4/:

$$K_0 = 0,00258$$

The equilibrium constant for iron carbonate was taken from The International Union of Pure and Applied Chemistry (IUPAC) with Institute for Energy Technology (IFE) ionic strength dependence, see /5/:

$$K_{\text{sp}} = 10^{-(10.13+0.0182 \cdot T_c - 2.44 \cdot I^{0.5} + 0.72 \cdot I)} \text{ molal}^2 \quad (13)$$

The other equilibrium constants have various origin. Crovetto has made an extensive compilation of data for the solubility of CO_2 in water as function of temperature and based on that found an equation which is valid from 0 °C to the critical point of water /6/. This equation is used as the basis for the Henry's law equation. The pressure dependence as given by Oddo and Tomson has been added together with an Institute for Energy Technology (IFE) expression for the ionic strength dependence /7/. The IFE equation is fitted to data by Cramer /8/. This Henry's law equation requires CO_2 fugacities as given by the equations given in 8.1.

0 °C – 80 °C:

$$K_H = 55.5084 \cdot e^{-(4.8 + \frac{3934.4}{T_K} - \frac{941290.2}{T_K^2})} \cdot 10^{-(1.790 \cdot 10^{-4} \cdot P + 0.107 I)} \text{ molar / bar} \quad (14)$$

80 °C – 200 °C:

$$K_H = 55.5084 \cdot e^{-(\frac{1713.53 \cdot (1 - \frac{T_K}{647})^{1/3}}{T_K} + 3.875 + \frac{3680.09}{T_K} - \frac{1198506.1}{T_K^2})} \cdot 10^{-(1.790 \cdot 10^{-4} \cdot P + 0.107 I)} \text{ molar / bar} \quad (15)$$

The dissociation constants for carbonic acid when the concentration of H_2CO_3 is set to the sum of dissolved CO_2 and H_2CO_3 , are based on equations given by Atkinson /9/ and Oddo and Tomson /7/:

$$K_1 = 10^{-(356.3094 + 0.06091964 \cdot T_K - \frac{21834.37}{T_K} - 126.8339 \cdot \text{Log}_{10}(T_K) + \frac{168491.5}{T_K^2} - 2.564 \cdot 10^{-5} \cdot P - 0.491 I^{0.5} + 0.379 I - 0.06506 I^{1.5} - 1.458 \cdot 10^{-3} \cdot I \cdot T_f)} \quad (16)$$

$$K_2 = 10^{-(107.8871 + 0.03252849 \cdot T_K - \frac{5151.79}{T_K} - 38.92561 \cdot \text{Log}_{10}(T_K) + \frac{563713.9}{T_K^2} - 2.118 \cdot 10^{-5} \cdot P - 1.255 I^{0.5} + 0.867 I - 0.174 I^{1.5} - 1.588 \cdot 10^{-3} \cdot T_f \cdot I)} \quad (17)$$

where P is the pressure given in psi.

The equation for the equilibrium constant for the dissociation of water was based on data given by Delahay/10/:

$$K_w = 10^{-(29.3868 - 0.0737549T + 7.47881 \times 10^{-5} T^2)} \quad \text{molar}^2 \quad (18)$$

8.3 Humidity

A prerequisite for corrosion to occur is that there is liquid water present in the system. In gas systems, an essential assessment is to determine if the presence of condensed water is possible. The program therefore includes a support function to calculate humidity in pure water /11/, i.e. in systems without glycol.

$$\text{Humidity (\%)} = 100 \times (P \times F_{H_2O}) / (p_{H_2O} \times F_{tot}) \quad (19)$$

The dew point temperature (T_{dew}) equals the temperature where the humidity is 100 %.

8.4 Wall shear stress

Wall shear stress is one of the parameters needed for calculation of corrosion rate. In the model, the mean wall shear stress in straight pipe sections is used.

Obstacles and other geometrical changes in the flow will give rise to higher shear stresses than calculated by this program. Further, different flow regimes and geometrical obstacles may generate shear stress fluctuations where the shear stress peaks may be considerably higher than the average shear stress.

High shear stress may cause mesa attacks, with corrosion rates significantly higher than what is estimated by this computer program.

It is not the objective of this computer program to cover all such eventualities, and the user of the program shall evaluate the flow effect in each system/part of a system based on expertise and available experience and documentation.

The mean wall shear on the wall at medium to high superficial velocities of one or both of the liquid and gas velocities:

$$S = 0,5 \times \rho_m \times f \times u_m^2 \quad (\text{Pa}) \quad (20)$$

where the friction factor, f , can be expressed as:

$$f = 0,001375 \left[1 + \left(20000 \frac{k}{D} + 10^6 \frac{\mu_m}{\rho_m u_m D} \right)^{0,33} \right] \quad (21)$$

Mixture density, velocity and viscosity is expressed as:

$$\begin{aligned} \rho_m &= \rho_L \times \lambda + \rho_G \times (1 - \lambda) \\ \rho_L &= \phi \times \rho_w + \rho_o \times (1 - \lambda) \\ \rho_G &= 2,7 \times 14,5 \times 16,018 \times P \times \text{specific gravity} / Z \times (460 + T_f) \end{aligned}$$

$$u_m = u_L^s + u_G^s$$

$$\begin{aligned} \text{The liquid is considered incompressible:} \quad u_L^s &= Q_L / A \\ \text{The gas superficial velocity is:} \quad u_G^s &= (Q_G / A) \times Z \times (T / T_{std}) \end{aligned}$$

$$\mu_m = \mu_L \times \lambda + \mu_G \times (1 - \lambda)$$

$$\lambda = \frac{Q_L}{Q_L + Q_G}$$

This model (see /12/) is verified for medium/high flow rates by tests.

If water is present the viscosity of the liquid is found as follows:

The effective viscosity of a kinetically stable oil/water mixture depends on the watercut /13/. Preferably the maximum magnitude of viscosity and the corresponding watercut should be known. The viscosity of the oil wet region, i.e. below the inversion point in a dispersed flow, can be represented as:

$$\mu_L = \mu_0 \left(1 + \frac{\frac{\phi}{B_0}}{1,187 - \frac{\phi}{B_0}} \right)^{2,5} \quad (\text{Ns/m}^2) \quad (22)$$

The value of B_0 for the maximum relative viscosity $\mu_{rel\max}$ (relative to the oil) and corresponding watercut at the inversion point, ϕ_c , is equal to:

$$B_0 = \frac{\phi_c}{1,187 \left(1 - \left(\frac{1}{\mu_{rel\max}} \right)^{0,4} \right)}$$

If not known, data for a medium viscosity oil/water dispersion will be used. This dispersion exhibits a maximum value of relative viscosity = 7,06 at a watercut of 0,5. The oil viscosity is equal to 0,0011 Ns/m² at 60 °C and the water viscosity is equal to 0,00046 Ns/m².

Above the inversion point, the viscosity of any dispersion is given as:

$$\mu_L = \mu_w \left(1 + \frac{\frac{1-\phi}{B_w}}{1,187 - \frac{1-\phi}{B_w}} \right)^{2,5} \quad (\text{Ns/m}^2) \quad (23)$$

where

$$B_w = \frac{1 - \phi_c}{1,187 \left(1 - \left(\frac{R}{\mu_{rel\max}} \right)^{0,4} \right)}$$

The viscosity of water is as default given as function of temperature, T_c , given in °C /11/:

0 °C - 20 °C:

$$\mu_w = 10^{1301/(998,333+8,1855(T_c-20)+0,00585(T_c-20)^2)-1,30233} \cdot 10^{-3} \quad (\text{Ns/m}^2) \quad (24)$$

20 °C - 150 °C (the formula is strictly only valid up to 100 °C, but used up to 150 °C in this context):

$$\mu_w = 1002 \left(10^{\frac{(1,3272 (20-T_C) - 0,001053 (T_C - 20)^2)}{(T+105)}} \right) 10^{-3} \text{ (Ns/m}^2\text{)} \quad (25)$$

For the medium viscosity oil at 60 °C , R is equal to 0,42.

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