2

Lubricant Viscosity

2.1 INTRODUCTION

For hydrodynamic lubrication, the viscosity, μ, is the most important characteristic of a fluid lubricant because it has a major role in the formation of a fluid film. However, for boundary lubrication the lubricity characteristic is important. The viscosity is a measure of the fluid's resistance to flow. For example, a low-viscosity fluid flows faster through a capillary tube than a fluid of higher viscosity. High-viscosity fluids are thicker, in the sense that they have higher internal friction to the movement of fluid particles relative to one another.

Viscosity is sensitive to small changes in temperature. The viscosity of mineral and synthetic oils significantly decreases (the oils become thinner) when their temperature is raised. The higher viscosity is restored after the oils cool down to their original temperature. The viscosity of synthetic oils is relatively less sensitive to temperature variations (in comparison to mineral oils). But the viscosity of synthetic oils also decreases with increasing temperature.

During bearing operation, the temperature of the lubricant increases due to the friction, in turn, the oil viscosity decreases. For hydrodynamic bearings, the most important property of the lubricant is its viscosity at the operating bearing temperature. One of the problems in bearing design is the difficulty of precisely predicting the final temperature distribution and lubricant viscosity in the fluid film of the bearing. For a highly loaded bearing combined with slow speed, oils of relatively high viscosity are applied; however, for high-speed bearings, oils of relatively low viscosity are usually applied.

The bearing temperature always rises during operation, due to friction-energy loss that is dissipated in the bearing as heat. However, in certain applications, such as automobile engines, the temperature rise is much greater, due to the heat of combustion. In these cases, the lubricant is subject to very large variations of viscosity due to changes in temperature. A large volume of research and development work has been conducted by engine and lubricant manufacturers to overcome this problem in engines and other machinery, such as steam turbines, that involve a high-temperature rise during operation.

Minimum viscosity is required to secure proper hydrodynamic lubrication when the engine is at an elevated temperature. For this purpose, a lubricant of high viscosity at ambient temperature must be selected. This must result in high viscosity during starting of a car engine, particularly on cold winter mornings, causing heavy demand on the engine starter and battery. For this reason, lubricants with less sensitive viscosity to temperature variations would have a distinct advantage. This has been the motivation for developing the multigrade oils, which are commonly used in engines today. An example of a multigrade oil that is widely used in motor vehicle engines is SAE 5W-30. The viscosity of SAE 5W-30 in a cold engine is about that of the low-viscosity oil SAE 5W, while its viscosity in the hot engine during operation is about that of the higher-viscosity oil SAE 30. The viscosity of synthetic oils is also less sensitive to temperature variations, in comparison to regular mineral oils, and the development of synthetic oils during recent years has been to a great extent motivated by this advantage.

It is important to mention that the viscosity of gases, such as air, reveals an opposite trend, increasing with a rise in temperature. This fact is important in the design of air bearings. However, one must bear in mind that the viscosity of air is at least three orders of magnitude lower than that of mineral oils.

2.2 SIMPLE SHEAR FLOW

In Fig. 2-1, simple shear flow between two parallel plates is shown. One plate is stationary and the other has velocity U in the direction parallel to the plate. The fluid is continuously sheared between the two parallel plates. There is a sliding motion of each layer of molecules relative to the adjacent layers in the x direction. In simple shear, the viscosity is the resistance to the motion of one layer of molecules relative to another layer. The shear stress, τ, between the layers increases with the shear rate, U/h (a measure of the relative sliding rate of adjacent layers). In addition, the shear stress, τ, increases with the internal friction between the layers; that is, the shear stress is proportional to the viscosity, μ, of the fluid.

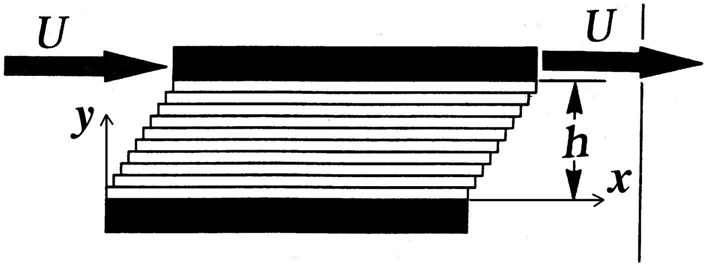

FIG. 2-1 Simple shear flow.

Most lubricants, including mineral and synthetic oils, demonstrate a linear relationship between the shear stress and the shear rate. A similar linear relationship holds in the air that is used in air bearings. Fluids that demonstrate such linear relationships are referred to as *Newtonian fluids*. In simple shear flow, $u = u(y)$, the shear stress, τ, is proportional to the shear rate. The shear rate between two parallel plates without a pressure gradient, as shown in Fig. 2-1, is U/h. But in the general case of simple shear flow, $u = u(y)$, the local shear rate is determined by the velocity gradient du/dy, where u is the fluid velocity component in the x direction and the gradient du/dy is in respect to y in the normal direction to the sliding layers.

One difference between solids and viscous fluids is in the relation between the stress and strain components. In the case of simple shear, the shear stress, τ, in a solid material is proportional to the deformation, shear strain. Under stress, the material ceases to deform when a certain elastic deformation is reached. In contrast, in viscous fluids the deformation rate continues (the fluid flows) as long as stresses are applied to the fluid. An example is a simple shear flow of viscous fluids where the shear rate, du/dy, continues as long as the shear stress, τ, is applied. For liquids, a shear stress is required to overcome the cohesive forces between the molecules in order to maintain the flow, which involves continuous relative motion of the molecules. The proportionality coefficient for a solid is the shear modulus, while the proportionality coefficient for the viscous fluid is the viscosity, μ. In the simple shear flow of a Newtonian fluid, a linear relationship between the shear stress and the shear rate is given by

$$\tau = \mu \frac{du}{dy} \tag{2-1}$$

In comparison, a similar linear equation for elastic simple-shear deformation of a solid is:

$$\tau = G \frac{de_x}{dy} \tag{2-2}$$

where e_x is the displacement (one-time displacement in the x direction) and G is the elastic shear modulus of the solid.

Whenever there is viscous flow, shear stresses must be present to overcome the cohesive forces between the molecules. In fact, the cohesive forces and shear stress decrease with temperature, which indicates a decrease in viscosity with an increase in temperature. For the analysis of hydrodynamic bearings, it is approximately assumed that the viscosity, μ, is a function of the temperature only. However, the viscosity is a function of the pressure as well, although this becomes significant only at very high pressure. Under extreme conditions of very high pressures, e.g., at point or line contacts in rolling-element bearings or gears, the viscosity is considered a function of the fluid pressure.

2.3 BOUNDARY CONDITIONS OF FLOW

The velocity gradient at the solid boundary is important for determining the interaction forces between the fluid and the solid boundary or between the fluid and a submerged body. The velocity gradient, du/dy, at the boundary is proportional to the shear stress at the wall. An important characteristic of fluids is that the fluid adheres to the solid boundary (there are some exceptions; oil does not adhere to a Teflon wall). For most surfaces, at the boundary wall, the fluid has identical velocity to that of the boundary, referred to as the *non-slip condition*. The intermolecular attraction forces between the fluid and solid are relatively high, resulting in slip only of one fluid layer over the other, but not between the first fluid layer and the solid wall. Often, we use the term *friction between the fluid and the solid*, but in fact, the viscous friction is only between the fluid and itself, that is, one fluid layer slides relative to another layer, resulting in viscous friction losses.

Near the solid boundary, the first fluid layer adheres to the solid surface while each of the other fluid layers is sliding over the next one, resulting in a velocity gradient. Equation (2-1) indicates that the slope of the velocity profile (velocity gradient) is proportional to the shear stress. Therefore, the velocity gradient at the wall is proportional to the shear stress on the solid boundary. Integration of the viscous shear forces on the boundary results in the total force caused by shear stresses. This portion of the drag force is referred to as the *skin friction force* or *viscous drag force* between the fluid and a submerged body. The other portion of the drag force is the *form drag*, which is due to the pressure distribution on the surface of a submerged body.

Oils are practically incompressible. This property simplifies the equations, because the fluid density, ρ, can be assumed to be constant, although this assumption cannot be applied to air bearings. Many of the equations of fluid mechanics, such as the Reynolds number, include the ratio of viscosity to density,

ρ, of the fluid. Since this ratio is frequently used, this combination has been given the name *kinematic viscosity*, ν:

$$\nu = \frac{\mu}{\rho} \tag{2-3}$$

The viscosity μ is often referred to as absolute viscosity as a clear distinction from kinematic viscosity.

2.4 VISCOSITY UNITS

The SI unit of pressure, p, as well as shear of stress, τ, is the Pascal (Pa) = Newtons per square meter [N/m^2]. This is a small unit; a larger unit is the kilopascal (kPa) = 10^3 Pa.

In the imperial (English) unit system, the common unit of pressure, p, as well as of shear stress, τ, is lbf per square inch (psi).

The conversion factors for pressure and stress are:

$$1\ \text{Pa} = 1.4504 \times 10^{-4}\ \text{psi}$$
$$1\ \text{kPa} = 1.4504 \times 10^{-1}\ \text{psi}$$

2.4.1 SI Units

From Eq. (2-1) it can be seen that the SI unit of μ is [N-s/m^2] or [Pa-s]:

$$\mu = \frac{\tau}{du/dy} = \frac{\text{N/m}^2}{(\text{m/s})/\text{m}} = \text{N-s/m}^2$$

The SI units of kinematic viscosity, ν, are [m^2/s]:

$$\nu = \frac{\mu}{\rho} = \frac{\text{N-s/m}^2}{\text{N-s}^2/\text{m}^4} = \text{m}^2/\text{s}$$

2.4.2 cgs Units

An additional cgs unit for absolute viscosity, μ, is the poise [dyne-s/cm^2]. The unit of dyne-seconds per square centimeter is the poise, while the centipoise (one hundredth of a poise) has been widely used in bearing calculations, but now has been gradually replaced by SI units.

The cgs unit for kinematic viscosity, ν, is the stokes (St) [cm^2/s]; a smaller unit is the centistokes (cSt), cSt = 10^{-2} stokes. The unit cSt is equivalent to [mm^2/s].

2.4.3 Imperial Units

In the imperial (English) unit system, the unit of absolute viscosity, μ, is the reyn [lbf-s/in.^{2}] (named after Osborne Reynolds) in pounds (force)-seconds per square inch. The imperial unit for kinematic viscosity, ν, is [in.^{2}/s], square inches per second.

Conversion list of absolute viscosity units, μ:

1 centipoise = 1.45×10^{-7} reyn
1 centipoise = 0.001 N-s/m^2
1 centipoise = 0.01 poise
1 reyn = 6.895×10^3 N-s/m^2
1 reyn = 6.895×10^6 centipoise
1 N-s/m^2 = 10^3 centipoise
1 N-s/m^2 = 1.45×10^{-4} reyn

2.4.4 Saybolt Universal Seconds (SUS)

In addition to the preceding units, a number of empirical viscosity units have been developed. Empirical viscosity units are a measure of the flow time of oil in a laboratory test instrument of standard geometry. The most common empirical viscosity unit in the United States is the Saybolt universal second (SUS). This Saybolt viscosity is defined as the time, in seconds, required to empty out a volume of 60 cm^3 of fluid through a capillary opening in a Saybolt viscometer. There are equations to convert this Saybolt viscosity to other kinematic viscosities, and the fluid density is required for further conversion to absolute viscosity, μ.

The SUS is related to a standard viscometer (ASTM specification D 88). This unit system is widely used in the United States by commercial oil companies. The following equation converts t (in SUS) into kinematic viscosity, ν, in centistoke (cSt) units:

$$\nu(\text{cSt}) = 0.22t - \frac{180}{t} \tag{2-4}$$

Lubrication engineers often use the conversion chart in Fig. 2-2 to convert from kinematic viscosity to absolute viscosity, and vice versa. Also, the chart is convenient for conversion between the unit systems.

2.5 VISCOSITY–TEMPERATURE CURVES

A common means to determine the viscosity at various temperatures is the ASTM viscosity–temperature chart (ASTM D341). An example of such a chart is given

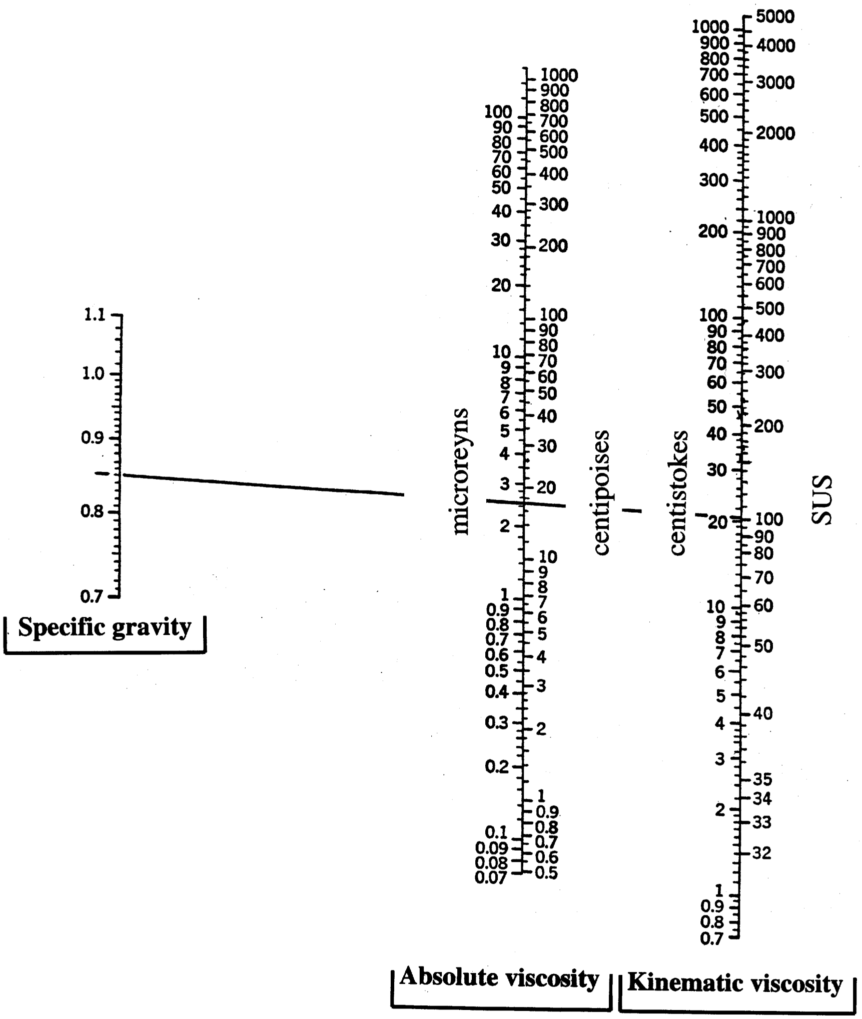

FIG. 2-2 Viscosity conversion chart from Saybolt universal seconds.

in Fig. 2-3. The viscosity of various types of mineral oils is plotted as a function of temperature. These curves are used in the design of hydrodynamic journal bearings.

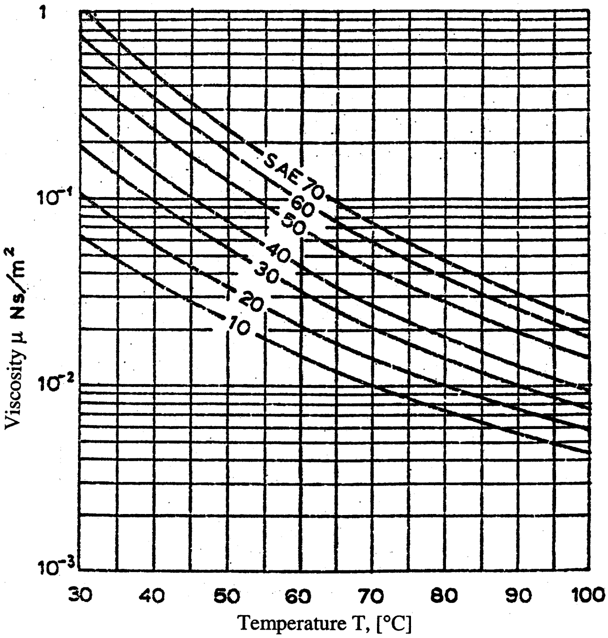

FIG. 2-3 Viscosity–temperature chart.

2.6 VISCOSITY INDEX

Lubricants having a relatively low rate of change of viscosity versus temperature are desirable, particularly in automotive engines. The viscosity index (VI) is a common empirical measure of the level of decreasing viscosity when the temperature of oils increases. The VI was introduced as a basis for comparing Pennsylvania and Gulf Coast crude oils. The Pennsylvania oil exhibited a relatively low change of viscosity with temperature and has been assigned a VI of 100, while a certain Gulf Coast oil exhibited a relatively high change in viscosity with temperature and has been assigned a VI of 0. The viscosity-versus-temperature curve of all other oils has been compared with the Pennsylvania and Gulf Coast oils. The viscosity index of all other oils can be determined from the slope of their viscosity–temperature curve, in comparison to $\mathrm{VI} = 0$ and $\mathrm{VI} = 100$ oils, as illustrated in Fig. 2-4. Demonstration of the method for determining the viscosity index from various viscosity–temperature curves is presented schematically in Fig. 2-4. The viscosity index of any type of oil is determined by the following equation:

$$\mathrm{VI} = \frac{L - U}{L - H} \times 100 \tag{2-5}$$

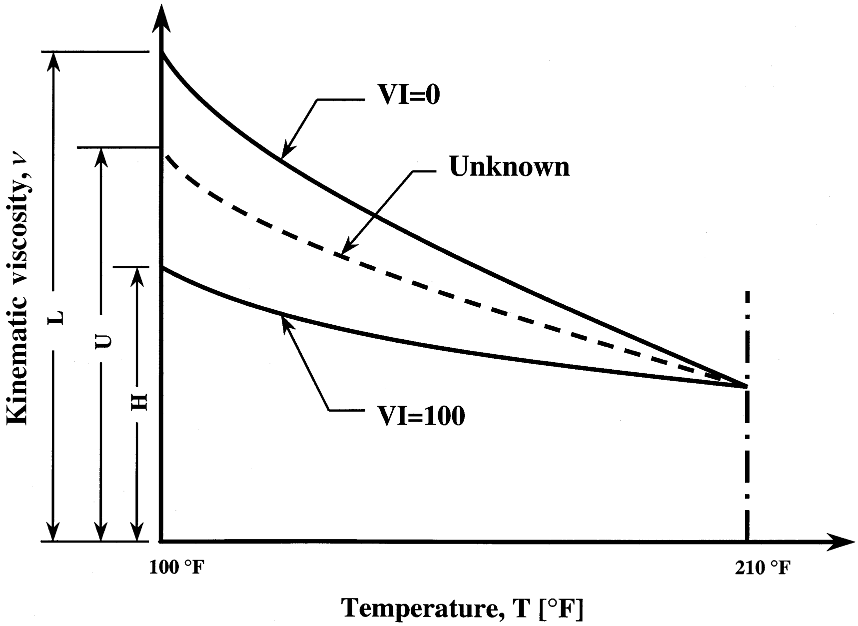

FIG. 2-4 Illustration of the viscosity index.

Here, L is the kinematic viscosity at 100°F of VI = 0 oil, H is the kinematic viscosity at 100°F of the VI = 100, and U is the kinematic viscosity at 100°F of the newly tested oil. High-viscosity-index oils of 100 or above are usually desirable in hydrodynamic bearings, because the viscosity is less sensitive to temperature variations and does not change so much during bearing operation.

2.7 VISCOSITY AS A FUNCTION OF PRESSURE

The viscosity of mineral oils as well as synthetic oils increases with pressure. The effect of the pressure on the viscosity of mineral oils is significant only at relatively high pressure, such as in elastohydrodynamic lubrication of point or line contacts in gears or rolling-element bearings. The effect of pressure is considered for the analysis of lubrication only if the maximum pressure exceeds 7000 kPa (about 1000 psi). In the analysis of hydrodynamic journal bearings, the viscosity–pressure effects are usually neglected. However, in heavily loaded hydrodynamic bearings, the eccentricity ratio can be relatively high. In such cases, the maximum pressure (near the region of minimum film thickness) can be above 7000 kPa. But in such cases, the temperature is relatively high at this region, and this effect tends to compensate for any increase in viscosity by pressure. However, in elastohydrodynamic lubrication of ball bearings, gears, and rollers, the maximum pressure is much higher and the increasing viscosity must be considered in the analysis. Under very high pressure, above 140,000 kPa (20,000 psi), certain oils become plastic solids.

Barus (1893) introduced the following approximate exponential relation of viscosity, μ, versus pressure, p:

$$\mu = \mu_0 e^{\alpha p} \tag{2-6}$$

Here, μ_0 is the absolute viscosity under ambient atmospheric pressure and α is the pressure-viscosity coefficient, which is strongly dependent on the operating temperature.

Values of the pressure-viscosity coefficient, α [m^2/N], for various lubricants have been measured. These values are listed in Table 2-1.

A more accurate equation over a wider range of pressures has been proposed by Rhoelands (1966) and recently has been used for elastohydrodynamic analysis. However, since the Barus equation has a simple exponential form, it has been the basis of most analytical investigations.

TABLE 2-1 Pressure-Viscosity Coefficient, α [m^2/N], for Various Lubricants

	Temperature, t_m		
Fluid	38°C	99°C	149°C
Ester	1.28×10^{-8}	0.987×10^{-8}	0.851×10^{-8}
Formulated ester	1.37	1.00	0.874
Polyalkyl aromatic	1.58	1.25	1.01
Synthetic paraffinic oil	1.77	1.51	1.09
Synthetic paraffinic oil	1.99	1.51	1.29
Synthetic paraffinic oil plus antiwear additive	1.81	1.37	1.13
Synthetic paraffinic oil plus antiwear additive	1.96	1.55	1.25
C-ether	1.80	0.980	0.795
Superrefined naphthenic mineral oil	2.51	1.54	1.27
Synthetic hydrocarbon (traction fluid)	3.12	1.71	0.937
Fluorinated polyether	4.17	3.24	3.02

Source: Jones et al., 1975.

2.8 VISCOSITY AS A FUNCTION OF SHEAR RATE

It has been already mentioned that Newtonian fluids exhibit a linear relationship between the shear stress and the shear rate, and that the viscosity of Newtonian fluids is constant and independent of the shear rate. For regular mineral and synthetic oils this is an adequate assumption, but this assumption is not correct for greases. Mineral oils containing additives of long-chain polymers, such as multigrade oils, are *non-Newtonian* fluids, in the sense that the viscosity is a function of the shear rate. These fluids demonstrate shear-thinning characteristics; namely, the viscosity decreases with the shear rate. The discipline of *rheology* focuses on the investigation of the flow characteristics of non-Newtonian fluids, and much research work has been done investigating the rheology of lubricants.

The following approximate power-law equation is widely used to describe the viscosity of non-Newtonian fluids:

$$\mu = \mu_0 \left| \frac{\partial u}{\partial y} \right|^{n-1} \qquad (0 < n < 1) \tag{2-7}$$

The equation for the shear stress is

$$\tau = \mu_0 \left| \frac{\partial u}{\partial y} \right|^{n-1} \frac{\partial u}{\partial y} \tag{2-8}$$

An absolute value of the shear-rate is used because the shear stress can be positive or negative, while the viscosity remains positive. The shear stress, τ, has the same sign as the shear rate according to Eq. (2-8).

2.9 VISCOELASTIC LUBRICANTS

Polymer melts as well as liquids with additives of long-chain polymers in solutions of mineral oils demonstrate viscous as well as elastic properties and are referred to as *viscoelastic fluids*. Experiments with viscoelastic fluids show that the shear stress is not only a function of the instantaneous shear-rate but also a memory function of the shear-rate history. If the shear stress is suddenly eliminated, the shear rate will decrease slowly over a period of time. This effect is referred to as *stress relaxation*. The relaxation of shear stress takes place over a certain average time period, referred to as the *relaxation time*. The characteristics of such liquids are quite complex, but in principle, the Maxwell model of a spring and a dashpot (viscous damper) in series can approximate viscoelastic behavior. Under extension, the spring has only elastic force while the dashpot has only viscous resistance force. According to the Maxwell model, in a simple shear flow,

$u = u(y)$, the relation between the shear stress and the shear rate is described by the following equation:

$$\tau + \lambda \frac{d\tau}{dt} = \mu \frac{du}{dy} \tag{2-9}$$

Here, λ is the relaxation time (having units of time). The second term with the relaxation time describes the fluid stress-relaxation characteristic in addition to the viscous characteristics of Newtonian fluids.

As an example: In Newtonian fluid flow, if the shear stress, τ, is sinusoidal, it will result in a sinusoidal shear rate in phase with the shear stress oscillations. However, according to the Maxwell model, there will be a phase lag between the shear stress, τ, and the sinusoidal shear rate. Analysis of hydrodynamic lubrication with viscoelastic fluids is presented in Chapter 19.

Problems

2-1a A hydrostatic circular pad comprises two parallel concentric disks, as shown in Fig. 2-5. There is a thin clearance, h_0 between the disks. The upper disk is driven by an electric motor (through a mechanical drive) and has a rotation angular speed ω. For the rotation, power is required to overcome the viscous shear of fluid in the clearance. Derive the expressions for the torque, T, and the power, $\dot{E}_f$, provided by the drive (electric motor) to overcome the friction due to viscous shear in the clearance. Consider only the viscous friction in the thin clearance, h_0, and neglect the friction in the circular recess of radius R_0.

For deriving the expression of the torque, find the shear stresses and torque, dT, of a thin ring, dr, and integrate in the boundaries from R_0 to R. For the power, use the equation, $\dot{E}_f = T\omega$. Show that the results of the derivations are:

$$T_f = \frac{\pi}{2} \mu \frac{R^4}{h_0} \left(1 - \frac{R_0^4}{R^4}\right) \omega \tag{P2-1a}$$

$$\dot{E}_f = \frac{\pi}{2} \mu \frac{R^4}{h_0} \left(1 - \frac{R_0^4}{R^4}\right) \omega^2 \tag{P2-1b}$$

2-1b A hydrostatic circular pad as shown in Fig. 2-5 operates as a viscometer with a constant clearance of $h_0 = 200$ mm between the disks. The disk radius is $R = 200$ mm, and the circular recess radius is $R_0 = 100$ mm. The rotation speed of the upper disk is 600 RPM. The lower disk is mounted on a torque-measuring device, which reads a torque of 250 N-m. Find the fluid viscosity in SI units.

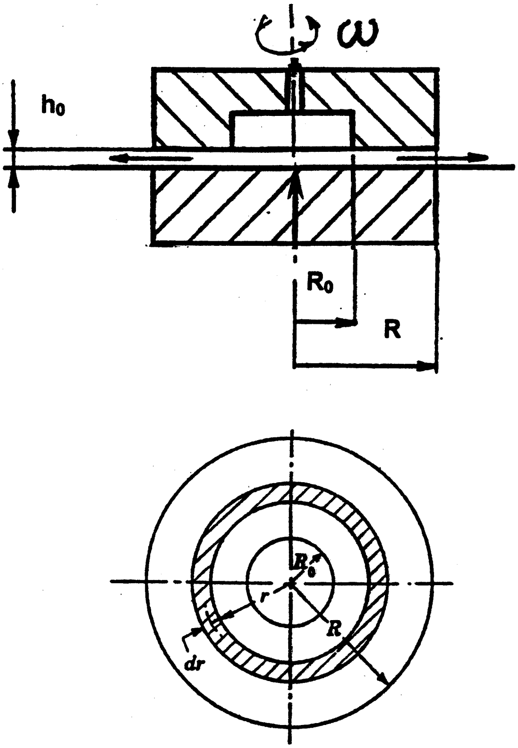

FIG. 2-5 Parallel concentric disks.

2-2 Find the viscosity in Reyns and the kinematic viscosity in centistoke (cSt) units and Saybolt universal second (SUS) units for the following fluids:

a. The fluid is mineral oil, SAE 10, and its operating temperature is 70°C. The lubricant density is $\rho = 860\ \text{kg/m}^3$.
b. The fluid is air, its viscosity is $\mu = 2.08 \times 10^{-5}\ \text{N-s/m}^2$, and its density is $\rho = 0.995\ \text{kg/m}^3$.
c. The fluid is water, its viscosity is $\mu = 4.04 \times 10^{-4}\ \text{N-s/m}^2$, and its density is $\rho = 978\ \text{kg/m}^3$.

2-3 Derive the equations for the torque and power loss of a journal bearing that operates without external load. The journal and bearing are concentric with a small radial clearance, C, between them. The diameter of the shaft is D and the bearing length is L. The shaft turns at a speed of 3600 RPM inside the bushing. The diameter of the shaft is $D = 50$ mm, while the radial clearance $C = 0.025$ mm. (In journal bearings, the ratio of radial clearance, C, to the shaft radius is of the order of 0.001.) The bearing length is $L = 0.5D$. The viscosity of the oil in the clearance is 120 Saybolt seconds, and its density is $\rho = 890\ \text{kg/m}^3$.

a. Find the torque required for rotating the shaft, i.e., to overcome the viscous-friction resistance in the thin clearance.
b. Find the power losses for viscous shear inside the clearance (in watts).

2-4 A journal is concentric in a bearing with a very small radial clearance, C, between them. The diameter of the shaft is D and the bearing length is L. The fluid viscosity is μ and the relaxation time of the fluid (for a Maxwell fluid) is λ. The shaft has sinusoidal oscillations with sinusoidal hydraulic friction torque on the fluid film:

$$M_f = M_0 \sin \omega t$$

This torque will result in a sinusoidal shear stress in the fluid.

a. Neglect fluid inertia, and find the equation for the variable shear stress in the fluid.
b. Find the maximum shear rate (amplitude of the sinusoidal shear rate) in the fluid for the two cases of a Newtonian and a Maxwell fluid.
c. In the case of a Maxwell fluid, find the phase lag between shear rate and the shear stress.