

Part I

Lubrication Theory





1

Properties of Lubricants

Many fluids serve as lubricants in industry. Among them, oil and grease are the most commonly used. Air, water and liquid metals are also used as special lubricants; for example, liquid sodium is often used as a lubricant in nuclear reactors. In some situations, solid lubricants, such as graphite, molybdenum disulfide or polytetrafluoroethylene (PTFE) can also be used. In this first chapter we will discuss the viscosity and density of lubricants, as they are the two important physical properties associated with lubrication.

In lubrication theory, the most important physical property of a lubricant is its viscosity, the most important factor in determining the lubrication film thickness. In hydrodynamic lubrication, the lubricant film thickness is proportional to the viscosity, while in elastohydrodynamic lubrication it is proportional to the viscosity to the powers 0.7. Although in boundary lubrication the viscosity does not directly influence the film thickness, the oil packages formed between peaks and valleys of roughness will carry part of the load. Therefore lubricant viscosity is closely related to its load-carrying capacity.

Furthermore, viscosity is also an important factor influencing the frictional force. A high-viscosity lubricant not only causes a lot of friction loss, but also produces a lot of heat, which make cooling control difficult. Because temperature rise caused by friction can lead to failure of the lubricant film, the surface will be worn increasingly. Therefore, a reasonable viscosity is required for practical lubrication.

The performance of elastohydrodynamic lubrication (EHL) also depends on the rheological characteristics of a lubricant. In point or line contacts, an EHL film is very thin, less than one micro-meter, but the pressure is very high, up to 1 GPa. And, because the contact area is often very small, the shear rate may be higher than 10^7 s^{-1} such that the passing time is very short, less than 10^{-3} s . Therefore, a friction process is always accompanied by high temperature. For such conditions, the properties of a lubricant are quite different from those of a Newtonian fluid. In such cases, therefore, it is necessary to study the rheological properties of lubricants. Experiments show that although the film thickness formula derived from the Newtonian fluid model is usually applied to the elastohydrodynamic lubrication, the frictional force and temperature calculated by a Newtonian fluid model will cause a large error. Therefore, in thermo-elastohydrodynamic lubrication (TEHL), more realistic non-Newtonian fluid models should be used. These belong to a lubricant rheology study which will not only help us understand the lubrication mechanism more deeply but also has major significance in energy conservation and improvement in the life of mechanical elements.

1.1 Lubrication States

The purpose of lubrication is to form a lubricant film to separate the friction surfaces to carry a load with a low shear stress to reduce friction and wear of materials. A lubricant film can be



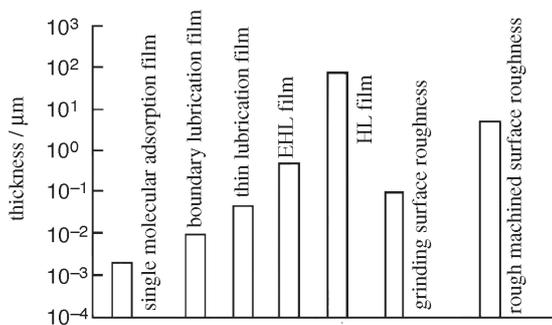
Table 1.1 Basic features of lubrication states.

Lubrication state	Typical film thickness	Formation method of lubricant film	Applications
Hydrodynamic lubrication	1–100 μm	A relative movement between friction surfaces forms a dynamic lubricant film	For surface contacts in high speed situations such as journal bearings
Hydrostatic lubrication	1–100 μm	Through an external pressure fluid form a lubricant film between friction surfaces	For surface contacts in low speed situations such as journal bearings and guides
Elastohydrodynamic lubrication	0.1–1 μm	Same as hydrodynamic lubrication	For point or line contacts in high speed situations, such as gears and rolling bearing
Thin film lubrication	10–100 nm	Same as hydrodynamic lubrication	For point or line contacts in low speed and high precision situations, such as precision rolling contact bearing
Boundary lubrication	1–50 nm	Physical or chemical reaction such as adsorption between lubricant molecules and metal surfaces	For low speed situations, such as journal bearings
Dry friction	1–10 nm	Surface oxide film, gas adsorbed film, etc.	For no lubrication or self-lubricating friction pairs

a liquid, a gas or a solid. According to the mechanisms of lubricant film formation, lubrication states can be divided into the following six basic types: (1) hydrodynamic lubrication; (2) hydrostatic lubrication; (3) elastohydrodynamic lubrication; (4) thin film lubrication; (5) boundary lubrication; and (6) dry friction. The features of the lubrication states are listed in Table 1.1.

A lubrication state has its typical film thickness. However, we cannot determine the lubrication state simply and accurately based on the thickness alone because the surface roughness also needs to be considered. Figure 1.1 lists the thickness orders of different lubricant films and roughnesses. Only when a lubricant film thickness is high enough is it possible to form a full film that will completely lubricate to avoid the peaks of the two rough surfaces contacting each other. If several lubrication states exist at the same time, this is known as mixed lubrication, as shown in Figure 1.2.

It is often inconvenient to determine a lubrication state based on lubricant film thickness because film thickness measurement is difficult. For convenience, the friction coefficient can

**Figure 1.1** Lubricant film thickness and roughness height.

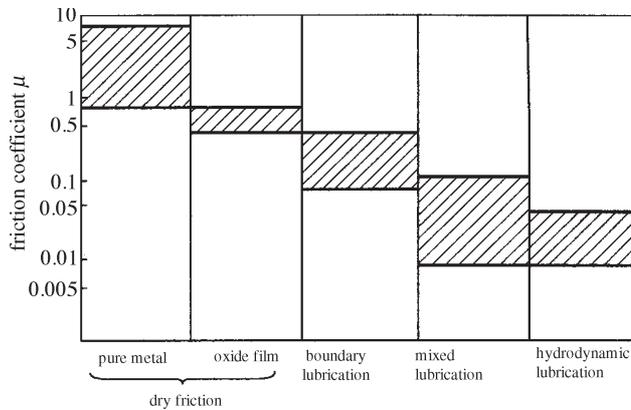


Figure 1.2 Typical friction coefficients of the lubrication states.

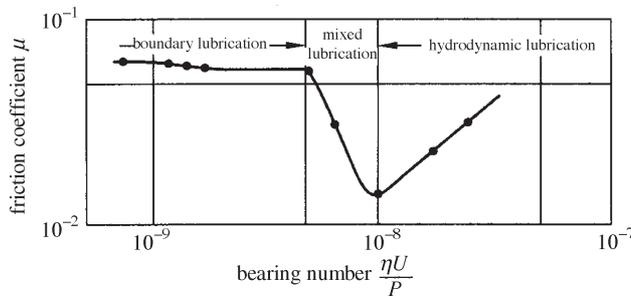


Figure 1.3 Stribeck curve of a journal bearing.

also be used to determine a lubrication state. Figure 1.2 presents some typical friction coefficients corresponding to the lubrication states.

With varying working conditions, one lubrication state may transform into another. Figure 1.3 gives a typical Stribeck curve of a journal bearing. The curves indicate the transformation of lubrication states corresponding with the working conditions. Here, the dimensionless bearing parameter ($\eta U/p$) reflects the working conditions, where η is the lubricant viscosity, U is the sliding velocity and p is the average pressure (carrying load per unit area).

It should be noted that methods of studying lubrication states may vary. For hydrodynamic lubrication and hydrostatic lubrication, theories of viscous fluid mechanics and heat transfer are necessarily used to analyze pressure and temperature distributions. As for elastohydrodynamic lubrication, elastic deformation of the contact surfaces and the rheological properties of lubricants must be added, while for boundary lubrication the perspectives of physical and chemical knowledge will help us understand the mechanisms of formation and failure of a boundary film. For dry friction, the main task is to avoid wear and tear. Therefore, its study involves material science, elastic and plastic mechanics, heat transfer, physical chemistry and so on.

1.2 Density of Lubricant

The density is one of the most common physical properties of a lubricant. A liquid lubricant is usually considered to be incompressible, and its thermal expansion is ignored so that the density is considered as a constant. Generally, the density of 20°C is considered the standard. In Table 1.2, the standard densities of some basic lubricants are given.

Table 1.2 Standard densities of some basic lubricants.

Lubricant	Density g/cm ³	Lubricant	Density g/cm ³
Triguaiacyl phosphate	0.915–0.937	water-soluble polyalkylene glycol	1.03–1.06
Diphenyl phosphate	0.990	non-water-soluble polyalkylene glycol	0.98–1.00
Hydroxymethyl-phenyl phosphate	1.161	dimethyl silicone oil	0.76–0.97
Hydroxymethyl-phenyl diphenyl phosphate	1.205	ethly-dimethyl silicone oil	0.95
Chlorinated diphenyl	1.226–1.538	phenyl-dimethyl silicone oil	0.99–1.10

The density of a lubricant is actually the function of pressure and temperature. Under some conditions, such as in the elastohydrodynamic lubrication state, the density of a lubricant should be considered to be variable.

The volume of lubricant is reduced with increase of pressure, so that its density increases. The relationship of density and pressure can be expressed as follows:

$$C = \frac{1}{\rho} \frac{d\rho}{dp} = \frac{V}{M} \frac{d(M/V)}{dp} = -\frac{1}{V} \frac{dV}{dp}, \quad (1.1)$$

where C is the compression coefficient; V is the volume of lubricant; M is the mass of lubricant.

The following well-known density equation is available:

$$\rho_p = \rho_0 [1 + C(p - p_0)], \quad (1.2)$$

where ρ_0 and ρ_p are the densities at pressures p_0 and p respectively.

The desirable C can be obtained from the following expression:

$$C = (7.25 - \lg \eta) \times 10^{-10}, \quad (1.3)$$

where η is the viscosity, mPa·s, and C is a constant, m²/N.

Conveniently, the following density and pressure relationship is often used in lubrication analysis:

$$\rho_p = \rho_0 \left(1 + \frac{0.6p}{1 + 1.7p} \right), \quad (1.4)$$

where p is the pressure, GPa.

The influence of temperature on density is due to thermal expansion, which increases the lubricant volume in order to decrease the density. If the thermal expansion coefficient of a lubricant is α_T , then

$$\rho_T = \rho_0 [1 - \alpha_T(T - T_0)], \quad (1.5)$$

where ρ_T is the density at temperature T ; ρ_0 is the density at temperature T_0 ; α_T is the constant, °C⁻¹.

Usually, α_T can be expressed in the following way. If the viscosity of a lubricant is less than 3000 mPa·s (i.e. $1g\eta \leq 3.5$), then

$$\alpha_T = \left(10 - \frac{9}{5} \lg \eta\right) \times 10^{-4}. \quad (1.6)$$

If the viscosity of a lubricant is greater than 3000 mPa·s (i.e. $1g\eta > 3.5$), then

$$\alpha_T = \left(5 - \frac{3}{8} \lg \eta\right) \times 10^{-4}. \quad (1.7)$$

1.3 Viscosity of Lubricant

Viscosity varies significantly with temperature and pressure. The properties of viscosity have a great influence on lubrication. In elastohydrodynamic lubrication, both the viscosity and density of a lubricant significantly vary with temperature and pressure.

1.3.1 Dynamic Viscosity and Kinematic Viscosity

Viscosity is the capability of a fluid to resist shear deformation. When a fluid flows on a solid surface, due to adhesion to the solid surface and the interaction between the molecules of the fluid, shear deformation of the fluid exists. Therefore, viscosity is the measurement of the resistance of the internal friction of a fluid.

1.3.1.1 Dynamic Viscosity

Newton first proposed the viscous fluid model. He considered that a fluid flow consists of many very thin layers. The adjacent layers slide relatively, as shown in Figure 1.4, where h is the thickness, U is the velocity of the moving surface, A is the area of the surface and F is the drawing force. Due to viscous friction within layers of the fluid, movement is transferred from one layer to the next. Because of viscosity, relative sliding between the layers results in shear stress, that is, friction within the fluid. The movement is transferred to the adjacent layer such that the faster layer is decelerated, but the slower layer is accelerated. This forms a velocity difference. If the surfaces A and B are parallel to each other, the distribution of the velocity u is linear, as shown in Figure 1.4.

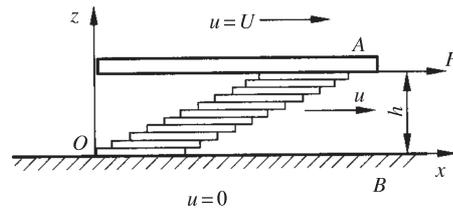
Newton assumed that the shear stress and shear rate are proportional to each other, which is known as Newton's viscosity law:

$$\tau = \eta \dot{\gamma}, \quad (1.8)$$

where τ is the shear stress, $\tau = F/A$; $\dot{\gamma}$ is the shear rate, that is

$$\dot{\gamma} = \frac{d\gamma}{dt} = \frac{d}{dt} \frac{dx}{dz} = \frac{d}{dz} \frac{dx}{dt} = \frac{du}{dz}. \quad (1.9)$$

Figure 1.4 Newtonian fluid flow.



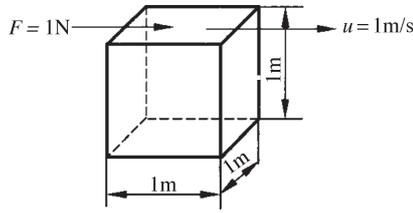


Figure 1.5 Viscosity definition.

From the above equation, we can see that the shear rate is equal to the gradient of the fluid flow velocity across the film thickness. Therefore, Newton's viscosity law can be written as

$$\tau = \eta \frac{du}{dz}, \quad (1.10)$$

where η is defined as the fluid dynamic viscosity.

Dynamic viscosity is the ratio of shear stress to shear rate. In the international system of units (SI), the unit of dynamic viscosity is $\text{N}\cdot\text{s}/\text{m}^2$ or $\text{Pa}\cdot\text{s}$, as shown in Figure 1.5.

In the CGS system often used in engineering, the dynamic viscosity unit is $\text{dyne}\cdot\text{s}/\text{cm}^2$ or P (Poise).

$$1 \text{ P} = 1 \text{ dyne}\cdot\text{s}/\text{cm}^2 = 0.1 \text{ N}\cdot\text{s}/\text{m}^2 = 0.1 \text{ Pa}\cdot\text{s}. \quad (1.11)$$

Because P is too large, 1% P or cP (centipoise) is often used.

If the imperial system is used, the unit of dynamic viscosity is Reyn.

$$1 \text{ Reyn} = 1 \text{ lbf}\cdot\text{s}/\text{in}^2 = 6.89476 \times 10^4 \text{ P}. \quad (1.12)$$

Dynamic viscosities of fluids vary over a wide range. The viscosity of air is 0.02 mPa·s, the viscosity of water is 1 mPa·s, while the viscosity of molten asphalt is up to 700 mPa·s. The viscosities of engineering lubricants usually range from 2 to 400 mPa·s. Fluids obeying Newton's viscosity law are called Newtonian fluids; in contrast, those that do not are known as non-Newtonian fluids. Under optimal working conditions, most mineral lubricating oils are considered Newtonian fluids.

1.3.1.2 Kinematic Viscosity

In engineering, kinematic viscosity is often used rather than dynamic viscosity. Kinematic viscosity is equal to the ratio of the dynamic viscosity of a fluid to its density. If the density is ρ and the dynamic viscosity is η , the kinematic viscosity ν is expressed as

$$\nu = \frac{\eta}{\rho}. \quad (1.13)$$

The unit of kinematic viscosity in SI is m^2/s , and in the CGS system of units it is the Stoke (St), $1 \text{ St} = 10^2 \text{ mm}^2/\text{s} = 10^{-4} \text{ m}^2/\text{s}$. Because St is too large, cSt (centi St) is more commonly used in practice; $1 \text{ cSt} = 1 \text{ mm}^2/\text{s}$.

As the densities of common mineral oils are usually in the range of 0.7–1.2 g/cm^3 , choosing the typical mineral oil density equal to 0.85 g/cm^3 , the following approximation can be conveniently used in engineering.

$$\eta = 0.85\nu \quad (1.14)$$

1.3.2 Relationship between Viscosity and Temperature

Viscosity of lubricants varies significantly with temperature. Generally, the higher the viscosity, the more sensitive the lubricant is to changes in temperature.

From a molecular viewpoint, fluid is composed of a large number of randomly moving molecules so that the viscosity of fluid is the result of gravitational forces and momentum of the molecules. The gravitational forces between the molecules significantly vary with the distance between molecules, while the momentum depends on velocity. As temperature rises, both the average molecular motion and average molecular distance of the fluid increase. This causes the momentum of molecules to increase, but the gravitational forces to decrease. Therefore, the viscosity of a liquid drops sharply with the increase of temperature and this significantly affects lubrication.

In order to accurately determine the lubrication performance, thermal analysis should be carried out to find out the variation of viscosity. Temperature calculation therefore becomes an important part of lubrication analysis. The influence of temperature on gas viscosity is commonly neglected although the viscosity of gas usually increases slightly with increase of temperature.

A lot of research into the relationships between viscosity and temperature has been carried out and, as a result, a number of formulas have been put forward. Some formulas are summaries of empirical data. To use these formulas, we must carefully consider their usage limitations.

1.3.2.1 Viscosity–Temperature Equations

Most lubricant viscosities drastically decline with increase of temperature. Their relationships are given in the following forms.

$$\text{Reynolds} \quad \eta = \eta_0 e^{-\beta(T-T_0)} \quad (1.15)$$

$$\text{Andrade–Eyring} \quad \eta = \eta_0 e^{\frac{a}{T}} \quad (1.16)$$

$$\text{Slotte} \quad \eta = \frac{s}{(\alpha + T)^m} \quad (1.17)$$

$$\text{Vogel} \quad \eta = \eta_0 e^{b/(T+\theta)}, \quad (1.18)$$

where η_0 is the viscosity under temperature T_0 ; η at temperature T ; β is the viscosity–temperature coefficient, approximately equal to $0.03 \text{ 1/}^\circ\text{C}$; $m=1, 2, \dots$; θ is the temperature of “infinite viscosity” and for a standard mineral oil, θ is desirably equal to 95°C ; a, s and b are constants.

In the above equations, the Reynolds viscosity–temperature equation is more convenient to be used, but the Vogel viscosity–temperature equation is more accurate.

1.3.2.2 ASTM Viscosity–Temperature Diagram

ASTM (American Society for Testing and Materials) suggests using viscosity index (VI) to describe the viscosity–temperature relationship and giving their corresponding viscosity–temperature diagram.

The relationship is

$$(v + a) = bd^{1/T^c}, \quad (1.19)$$

where v is the kinematic viscosity, mm^2/s ; T is the absolute temperature; a, b and d are constants, $a = 0.6\text{--}0.75$, $b = 1$, $d = 10$.

For double logarithmic coordinates and single logarithmic abscissa, the formula is a straight line, as shown in Figure 1.6.

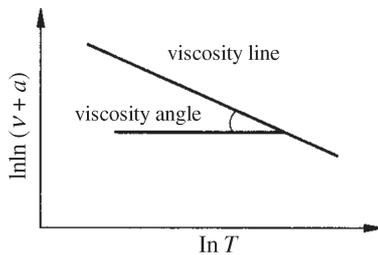


Figure 1.6 ASTM diagram.

Then, Equation 1.19 becomes

$$\ln \ln(\nu + a) = A - B \ln T. \quad (1.20)$$

The advantage of Equation 1.20 is that only two viscosities at the corresponding temperatures need to be measured in order to determine the constants A and B . Then a straight line can be plotted to find other viscosities at any temperature.

For a typical mineral oil, an ASTM diagram is very effective. Furthermore, the viscosity angle in the diagram can be used as an index to evaluate the viscosity–temperature feature of a lubricant.

1.3.2.3 Viscosity Index

The viscosity index (VI) is used to represent variation of viscosity. Its expression is

$$VI = \frac{L - U}{L - H} \times 100. \quad (1.21)$$

In order to obtain VI experimentally, measure the kinematic viscosity $\nu_{210^\circ\text{F}}$ of the oil to be tested at 210°F ($\approx 85^\circ\text{C}$) first. Then select two standard oils having the same measured viscosity $\nu_{210^\circ\text{F}}$ at 210°F , but with VI s equal to 0 and 100 respectively. Then measure the kinematic viscosities ν of the oil and the two standard oils at 100°F ($\approx 38^\circ\text{C}$). If these kinematic viscosities are respectively represented by U , L and H , VI of the oil to be tested can be calculated by Equation 1.21.

VI s of some lubricating oils are given in Table 1.3.

As the larger the VI , the less the variation of viscosity with temperature, a lubricating oil with a large VI possesses a good viscosity–temperature property.

1.3.3 Relationship between Viscosity and Pressure

With increase of pressure, the distance between molecules of a fluid decreases such that its viscosity increases. Experiments show that when pressure is higher than 0.02 GPa, the viscosity of a mineral oil will obviously increase. Under a pressure of 1 GPa, the viscosity of a mineral oil is several orders larger than at atmospheric pressure. If pressure rises higher, a mineral oil may lose some of its liquid properties and become like a wax. Therefore, the viscosity–pressure

Table 1.3 VI of some lubricating oils.

Lubricant	VI	$\nu_{100^\circ\text{F}}$ (mm^2/s)	$\nu_{210^\circ\text{F}}$ (mm^2/s)
Mineral oil	100	132	14.5
Multi-grade oil 10W/30	147	140	17.5
Silicon oil	400	130	53