

Chapter 10

Fundamentals of Lubrication

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Abstract Lubricants are substances used to minimize the friction and wear of moving parts. Additionally, they can serve to distribute heat, remove contaminants, and improve the efficiency and lifetime of mechanical systems. Lubricants can generally be categorized as liquid, solid, or gaseous. Liquid lubricants consist of base oils such as natural oils, mineral (petroleum) oils, and synthetic oils with combinations of additives that further enhance the properties of the lubricants. Solid or dry lubricants are generally powders or semisolids in the form of a grease or solid–liquid suspension. Gaseous lubricants have a much lower viscosity than liquid or solid lubricants and utilize gasses such as air under pressure. The selection of an appropriate lubricant for a mechanical system requires a thorough understanding of the rheology of lubricants, the effects of additive combinations, and the knowledge of lubrication theory. Lubrication theory is linked to numerous fields of expertise outside of tribology, and without this interdisciplinary aspect, the progression of lubricants and lubrication technologies within the vast array of applications may not have reached the necessary levels of success. The use of liquid lubricants is ubiquitous in most applications, ranging from automotive fluids, to industrial oils, and process oils. Within the lubrication industry, there are over 10,000 different lubricants used around the world. This chapter explores the many aspects of lubricants and lubrication technologies including lubrication fundamentals, rheology of liquid lubricants, liquid lubricant additives, and liquid lubrication theory.

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1 Lubrication Fundamentals

1.1 Introduction

A lubricant is a substance introduced between two moving surfaces to reduce friction, minimize wear, distribute heat, remove contaminants, and improve efficiency. The importance of lubricants and sustainable lubrication systems cannot be fully appreciated until understanding the implications of not using an appropriate lubricant or a lubricant at all. In 1979, it was estimated that over \$200 billion was spent in North America on machine maintenance [1]. Within the \$200 billion, approximately one-third (\$66.7 billion) could have been avoided with the use of adequate lubricants. More recently, estimates claim that the amount of energy wasted due to insufficient knowledge applied to the science of friction, lubrication, and wear resulted in roughly 0.4 % of the gross domestic product (GDP) being wasted [2]. In the United States, this means that over \$60.36 billion of the \$15.08 trillion GDP was wasted due to energy loss [3]. When considering the many applications that utilize lubricants such as internal combustion engines, turbines, hydraulic systems, compressors, vehicle and industrial gearboxes, and journal and thrust bearings, it becomes easy to understand the importance that lubricants play in the compliance, effectiveness, and operation of many of these applications.

Within the lubrication market, there are a vast number of applications which require specifically formulated lubricants that have given rise to the upwards of 10,000 different lubricants that satisfy more than 90 % of all lubricant applications worldwide [2]. Figure 10.1 dissects the global lubrication market as of 2004, which consumed roughly 37.4 million tons of lubricant [2]. This figure illustrates how automotive and industrial lubricants are the most prevalent. Industrial lubricants amount to 32 % and were composed of 12 % hydraulic oils, 10 % other industrial oils, 5 % metalworking fluids, 3 % greases, and 2 % industrial gear oils [4, 5].

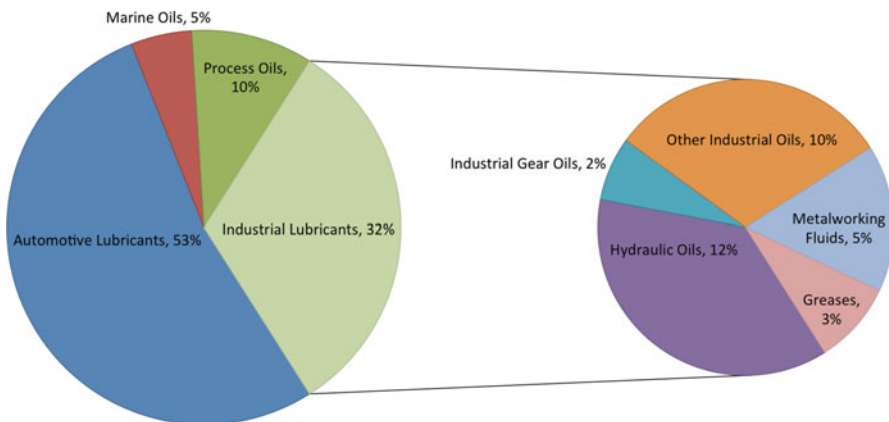


Fig. 10.1 2004 worldwide lubrication consumption [2]

The 10 % of other industrial oils within the industrial lubricants section consist of a wide range of lubricants such as air and gas compressor oils, bearing and circulating system oils, refrigerator compressor oils, and steam and gas turbine oils. In the automotive lubricants section, the most commonly used liquid lubricants were engine oils (petrol and diesel engine oils), automatic transmission fluids, gearbox fluids, brake fluids, and hydraulic fluids.

Lubricants originally consisted of natural oils and fats derived from plant- and animal-based raw materials which date back to 1400 BC. The modern lubrication market developed after the first oil well was drilled in 1959 in Titusville, PA. Since then, lubricants have evolved from mineral oils to petrochemically modified synthetic oils arriving in the 1960s to today's bio-based lubricants harvested from raw materials derived from the oleo-chemical industry. Recently, bio-based lubricants have begun to seek prominence for their environmental friendliness and superior tribological properties. The current trend in the lubrication industry is to develop more bio-based lubricants due to estimates indicating that nearly 50 % of all lubricants sold worldwide pollute the environment, through spillage, evaporation, and total loss applications [6]. An example of lubrication pollution is that of the diesel engine particulate emissions, where approximately one-third of the engine oil vaporizes, thus polluting the atmosphere. The large quantity of lubricant loss into the environment is the reason behind the development of environmentally friendly lubricants. Although the lubrication market is shifting to become more environmentally responsible by reducing the use of petroleum-based lubricants due to concerns of protecting the environment, depletion of oil reserves, and increases in oil price, mineral oil remains to be the largest constituent and the foundation to most lubricants [6].

Lubricants generally consist of about 90 % base oils, less than 10 % additives, and minute portions of other components. The exact formulation of a lubricant is typically linked to the specific application or intended use designated by the lubricant manufacture. Lubricants vary dramatically due to the wide functionality of a lubricant to dissolve or transport foreign particles, carrying away contaminants and debris, prevent corrosion or rust, seal clearances, dissipate heat, and minimize friction and wear of components. In general, there are three categories of lubricants: liquid, solid, and gaseous.

1.1.1 Liquid Lubricants

Liquid lubricants may be characterized in a variety of methods and the most common method is by the type of base oil used. Notable base oil types are lanolin (wool grease, a natural water repellent), water, mineral oils (derived from crude oil), vegetable oils (derived from plants and animals), and synthetic oils (consisting of oleo-chemical compounds synthesized from compounds other than crude oil) [7]. Liquid lubricants are often viscous fluids that require circulatory pumping systems or rotary mechanical systems such as bearings or gears to distribute the fluid through the various machine elements. The primary function of a liquid lubricant is to control friction, wear, and surface damage over the intended life of

a system. Secondary functions of liquid lubricants are to prevent corrosion and remove heat, dirt, and wear debris. In some instances, liquid lubricants are used to transfer either force or energy as in hydraulic systems.

1.1.2 Solid Lubricants

Solid or dry lubricants are generally powders or semisolids in the form of a grease or solid–liquid suspension. Some of the commonly known powder lubricant materials are graphite (C), molybdenum disulphide (MoS_2), tungsten disulphide (WS_2), and titanium dioxide (TiO_2) [8–14]. Solid lubricants offer lubrication at temperatures (up to 350 °C) that are higher than many liquid oil-based lubricants. Solid lubricants such as Teflon or PTFE (polytetrafluoroethylene) are typically used as a coating layer to provide a nonstick surface [15].

Solid–liquid suspensions consist of solid lubricants mixed into a liquid fluid such as water or oil to form a colloidal suspension. These slurry or two-phase lubricants are often utilized in metalworking processes such as forging and extrusion. Solid lubricants can also be used in a less viscous approach where they are applied as suspension in a carrier fluid such as vegetable oil [6, 16, 17].

Greases are complex semisolid lubricants consisting of liquid-base oils mixed with various thickening agents derived from soaps or other organic or inorganic substances [18]. Greases can also include a multitude of additives such as powder lubricants and their consistency closely resembles that of a paste [19]. They range in multiple viscosities and are available in semisolid (synonymous with semiliquid) form to solid form known as block greases. Greases are often processed in special grease-making facilities, as they require special equipment for their production.

1.1.3 Gaseous Lubricants

Gaseous lubricants have a much lower viscosity than liquid or solid lubricants. Gaseous lubricants also exhibit lower heat capacity and higher compressibility than liquid or solid lubricants [7]. Some examples of gaseous lubricants are air, technical gases, steam, and liquid-metal vapors. Gaseous lubricants can be found in foil bearings, where centripetal forces allow air to push the foil away from the shaft so that there is minimal contact. Another example is air hockey tables, a popular game at arcades, which utilizes compressed air to establish a thin air cushion on which the puck glides over allowing for a quasi-frictionless environment.

1.2 Lubricant Additives

Additives are substances used to improve the performance of lubricants. Additives are selected based on their ability to reduce friction and wear, increase viscosity, improve viscosity index, resist corrosion and oxidation, increase component and

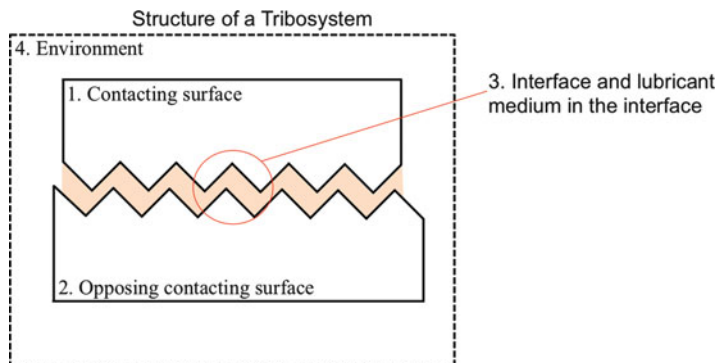


Fig. 10.2 Structure of a tribosystem: (1) contacting surface, (2) opposing contacting surface, (3) interface and lubricant medium in the interface, and (4) environment

lubricant lifetime, and minimize contamination [20]. The main categories of additives are antioxidants, antiwear formulations, antifoaming agents, corrosion inhibitors, detergents (demulsifying/emulsifying), extreme pressure, friction modifiers, metal deactivators, and viscosity index improvers [1].

1.3 Lubrication Regimes

Lubricants are used to reduce the frictional force between surfaces, known as a tribological system. A tribological system (or tribosystem) consists of four components as described in Fig. 10.2: (1) a contacting surface, (2) an opposing contacting surface, (3) the contacting interface along with the lubricant medium in the interface, and (4) the environment and all external properties [2, 21, 22]. Tribosystems can consist of numerous components and systems. For example, a plain bearing is a tribosystem. In this example, the material pair is the shaft and bearing shell, with the lubricant located in the annular gap. Other examples of material pairs that form tribosystems are in combustion engines such as the piston rings and cylinder wall and the camshaft lobes and tappets [7]. In metalworking, the tool and the workpiece also constitute as a material pair forming a tribosystem.

A lubricant functions by introducing a medium with a lower shear strength than the opposing surfaces. In some lubricated tribosystems, the lubricant may not completely prevent asperity contact between the surfaces. However, the lubricant will reduce the number of asperity contacts and it may also reduce the shear strength of the junctions formed during asperity contact. In other cases, the lubricant completely separates the surfaces and no asperity contacts are formed at all. Lubrication regimes are normally associated with dominant lubrication mechanisms involved in the mechanical system as illustrated in the Stribeck curve as shown in Fig. 10.3 [2] for liquid lubrication. The three main lubrication

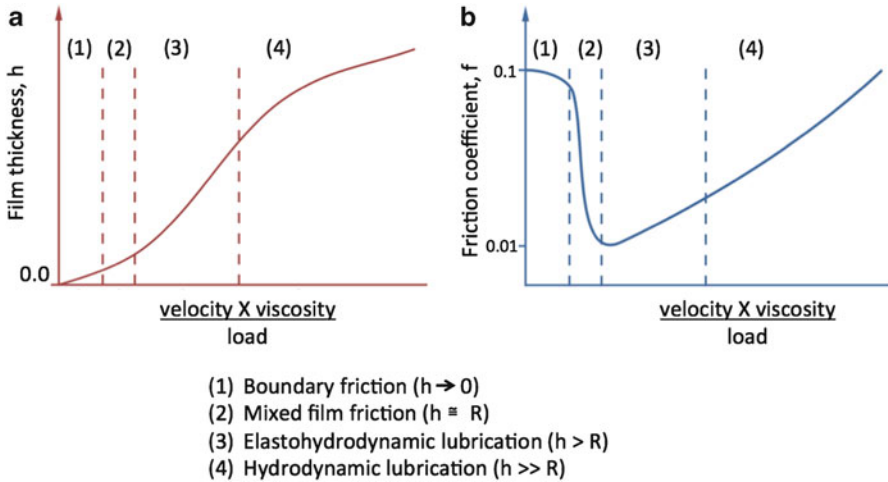
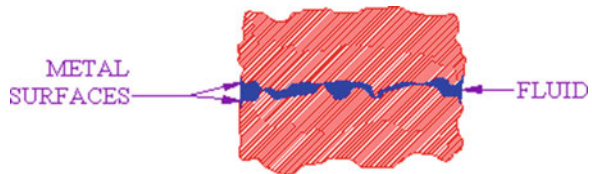


Fig. 10.3 Demarcation of lubrication regimes: (a) film thickness vs. Hersey's number and (b) coefficient of friction vs. Hersey's number (i.e., Stribeck curve)

Fig. 10.4 Boundary lubrication at the interface of a tribosystem

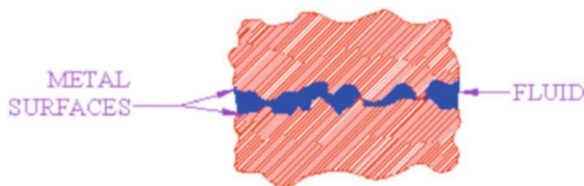


regimes can be referred to as boundary lubrication, mixed/elastohydrodynamic lubrication, and hydrodynamic lubrication.

1.3.1 Boundary Lubrication

Boundary lubrication or boundary friction is the lubrication regime with the most asperity contact between the surfaces occurring due the presence of a thin fluid film graphically depicted in Fig. 10.3a and illustrated in Fig. 10.4. Boundary lubrication is a complex process and is controlled by additives in the oil that form a thin molecular layer (monolayer) of fluid film through physical adsorption, chemisorption, and tribochemical reactions on the contacting surfaces [23]. One of the more common boundary lubrication additives are fatty acids which adhere to the metallic surfaces and form a tightly packed monolayer [24, 25]. This monolayer helps to reduce the asperity contacts that lead to high values of friction and wear. The development of a monolayer film is vital in boundary lubrication because in many practical applications, thick, long-lasting, lubricant films cannot be sustained between opposing surfaces and thus these monolayer films help to reduce the amount of surface interaction [20].

Fig. 10.5 Mixed lubrication/ elasto-hydrodynamic lubrication at the interface of a tribosystem



1.3.2 Mixed/Elastohydrodynamic Lubrication

Mixed film lubrication is the combination of full film hydrodynamic lubrication and boundary lubrication. In this lubrication regime, the surfaces are transitioning away from boundary lubrication into hydrodynamic lubrication where there may be frequent asperity contacts, but at least a portion of the bearing surface remains supported partially by a hydrodynamic film [23] as shown in Fig. 10.5. In mixed lubrication, the effects of monolayers formed by physical absorption, chemisorption, and chemical reaction remain critical to prevent unwanted adhesion during the asperity contacts [2].

Elastohydrodynamic (EHD) lubrication is a subset of hydrodynamic (HD) lubrication in which the elastic deformation of the contacting solids plays a significant role in the HD lubrication process. The film thickness in EHD lubrication is thinner (typically 0.5–5 μm) than that in HD lubrication and the load is still primarily supported by the EHD film [23]. In this transitional region, there is less asperity contact than that of mixed lubrication with more of the contacting surfaces being supported by the hydrodynamic fluid film.

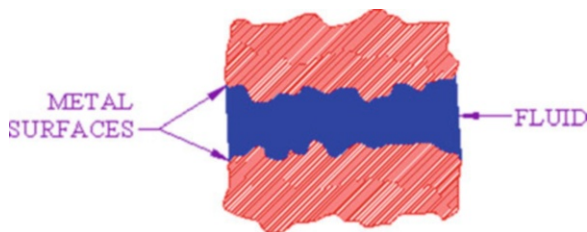
1.3.3 Hydrodynamic Lubrication

Hydrodynamic lubrication also known as fluid-film or thick-film lubrication involves two nonparallel surfaces in relative motion with a layer of fluid pulled in between the surfaces to develop adequate hydrodynamic pressure to support the load of the opposing surfaces and prevent asperity contact [2]. In this lubrication regime, the surfaces are no longer in contact as illustrated in Fig. 10.6 and the fluid has established itself in significant form to create a thick film.

1.4 Stribeck Curve

The Stribeck curve shown in Fig. 10.3b is a plot of the coefficient of friction against a nondimensional number known as Hersey's number (also referred to as the Stribeck number). Hersey's number was instrumental in demarcation of the aforementioned lubrication regimes [23]. Hersey's number is given by $(\eta v/p)$, where " η " is the lubricant viscosity, " v " is sliding velocity, and " p " is load per unit width.

Fig. 10.6 Hydrodynamic lubrication at the interface of a tribosystem



The values of the coefficient of friction that are depicted in the original Stribeck curve remain constant when Hersey's number approaches zero in the boundary lubrication regime. Experimental work done by Fischer et al. [26] led to the modification of the Stribeck curve. They showed that the coefficient of friction does not remain constant in the boundary lubrication regime, but reduces as the value of Hersey's number increases. The slope of this curve is determined by the efficiency of the boundary lubricant. At low values of Hersey's number, the thickness of the lubricant film, h , develops much less than the surface roughness, R . In boundary lubrication (illustrated in Fig. 10.4), thin monolayers develop causing the film thickness to approach zero, resulting in significant asperity contact and high friction. An increase in sliding speed or a decrease in load at constant viscosity can cause the film thickness to steadily increase therefore shifting the lubrication regime from boundary lubrication into mixed or elastohydrodynamic lubrication. This transition results in lower coefficient of friction values and thicker hydrodynamic fluid films. In the mixed lubrication regime, the fluid-film thickness can be on the same order of magnitude as the surface roughness ($h \cong R$), and in the elastohydrodynamic lubrication regime, the fluid-film thickness can be greater than the surface roughness ($h > R$). As the sliding speed continues to increase or the load decreases with a constant viscosity, this allows progress through the elastohydrodynamic regime allowing a full uninterrupted fluid film to develop that is significantly thicker than the surface roughness ($h \gg R$). When the fluid film is much greater than the surface roughness, then the hydrodynamic lubrication regime dominates. In this lubrication regime, internal friction in the lubricating film adds to external friction causing the coefficient of friction to increase as shown in Fig. 10.4.

Other methods have been proposed to quantify the various lubrication regimes. The Hamrock and Dowson model provided a formula for calculation of minimum film thickness in lubricated contacts [27–30]. The fluid-film thickness parameter, λ , decides the lubrication regime with boundary lubrication characterized by a value of λ less than 1, mixed or elastohydrodynamic lubrication described as $1 \leq \lambda \leq 3$, and hydrodynamic lubrication characterized by a value of λ greater than 3 [7, 20, 23, 31–34]. The fluid-film thickness parameter, λ , given in (10.1a), is the ratio of fluid-film thickness, h , and the composite surface roughness, σ :

$$\lambda = \frac{h}{\sigma} \quad (10.1a)$$

$$\sigma = \sqrt{\sigma_1^2 + \sigma_2^2} \quad (10.1b)$$

In (10.1a), the composite surface roughness is given in (10.1b) where σ_1 and σ_2 are RMS roughness of the two mating surfaces. The calculation of minimum film thickness for metals and polymers are presented in various publications throughout the literature [35–39].

2 Rheology of Liquid Lubricants

The characteristics of lubricants and their properties involve understanding the rheology of liquid lubricants. Many of the important characteristics of a lubricant include viscosity, consistency, flow properties, thermal stability, oxidative properties, and physiochemical properties.

2.1 Viscosity

Viscosity of a fluid may be defined as its resistance to flow. Different oils exhibit different viscosities. An example shown in Fig. 10.7 compares the viscosities of honey (~2,000 cP) and water (~1 cP) at 21 °C. If one examines honey in a jar and tries to pour it, the honey will move much more lethargically, whereas if one tries to pour water out of a jar, it readily pours. The difference between the two is that honey has a much higher viscosity and thus it is much more resistant to flow than water. Lubricant viscosity changes with temperature, load, shear rate, and pressure. Viscosity is important in the selection process of oils, because many oils have similar characteristics, but their viscosities differ. Viscosity directly relates to a lubricant's film strength and ability to keep moving parts separated.

The importance of proper viscosity selection is vital for the success of many lubrication systems. If an application operates at high speeds, low loads, and low temperatures, then it is generally accepted to use a low-viscosity lubricant.

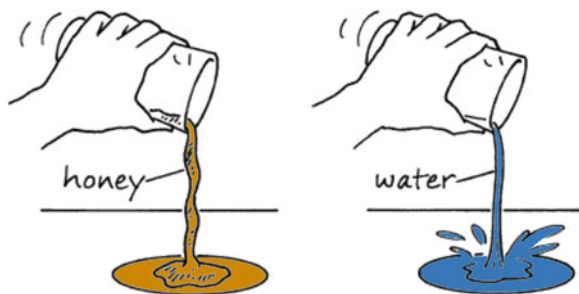
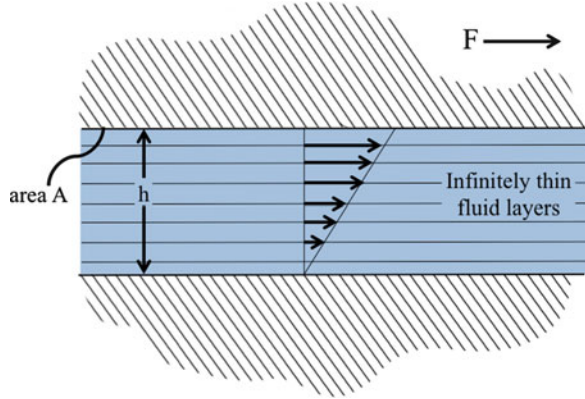


Fig. 10.7 Viscosity characteristics of honey and water. Honey is much more viscous than water

Fig. 10.8 Schematic of two parallel planes in relative motion with a velocity u , separated by a fluid film of thickness h with a linear velocity gradient [40]



Conversely, if an application operates at low speeds, high loads, and high temperatures, then higher viscous lubricants should be utilized [2]. Quantifying viscosity requires the use of two parameters, dynamic and kinematic viscosity, which will be addressed in the following sections.

2.2 Dynamic Viscosity

Dynamic viscosity can be explained by considering two parallel surfaces separated by a layer of fluid having a thickness h as demonstrated in Fig. 10.8. To move the upper surface, a force F is required which is proportional to the surface area A of the upper surface and the linear velocity s , as revealed in (10.2):

$$F \propto A \times u \quad (10.2)$$

Assuming that the fluid film separating the parallel surfaces is made up of a number of infinitely thin layers, the force needed to move the upper surface is thus proportional to

$$F \propto A \times \frac{u}{h} \quad (10.3)$$

Different fluids exhibit different proportionality constants η , known as the dynamic viscosity:

$$F = \eta \times A \times \frac{u}{h} \quad (10.4)$$

Rearranging (10.4) yields

$$\eta = \frac{F}{A} / \frac{u}{h} \quad (10.5a)$$

or

$$\eta = \tau / \frac{u}{h} \quad (10.5b)$$

where:

η is the dynamic viscosity (Pas),

τ is the shear stress acting on the fluid (Pa),

u/h is the shear rate, i.e., velocity gradient normal to the shear stress (s^{-1}).

Prior to the introduction of the international system (SI) of units of measure, the most commonly used dynamic viscosity unit was the Poise (P). However, for many practical applications, the Poise was far too large; thus a smaller unit, the centipoise (cP), was adopted as the standard unit. The SI unit for dynamic viscosity is Pascal-second (Pas). The relationship between Poise and Pascal-second is as follows: $1 \text{ (P)} = 100 \text{ (cP)} \approx 0.1 \text{ (Pas)}$.

2.3 Kinematic Viscosity

Kinematic viscosity is defined as the ratio of a fluid's dynamic viscosity divided by its density:

$$\nu = \frac{\eta}{\rho} \quad (10.6)$$

In (10.6), ν is the kinematic viscosity (m^2/s), η is the dynamic viscosity (Pas), and ρ is the fluid density (kg/m^3). Kinematic viscosity is often described in units of Stoke (S). This unit is also too large for many applications; thus a smaller unit, the centistoke (cS), is more commonly used. The SI unit for kinematic viscosity is m^2/s , with the following conversions: $1 \text{ S} = 100 \text{ cS} = 0.0001 \text{ m}^2/s$.

As previously mentioned, viscosity is dependent on temperature. Figure 10.9 profiles various lubricant viscosities over a broad range of temperatures revealing the relationship that as temperature increases, viscosity generally decreases [23, 40].

Ultimately, when choosing a lubricant based on viscosity, it is important that the lubricant is viscous enough to adequately provide a continuous fluid film in the contacting interface, but not too viscous as to create fluid friction due to viscous shearing. Viscous shearing is the phenomenon that occurs when the oil is too thick for a given application and the shear planes or layers of the fluid begin to drag over one another causing increased fluid friction also known as churning. As shown in

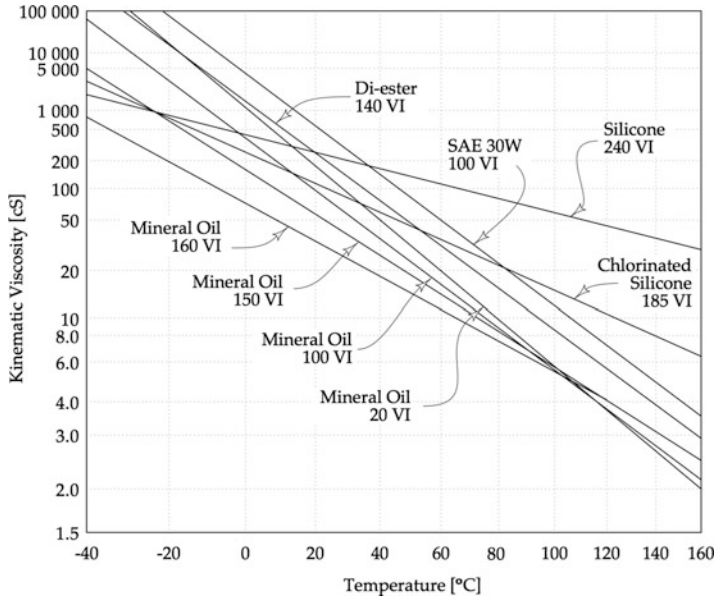


Fig. 10.9 Viscosity–temperature characteristics of selected oils [41, 42]

Fig. 10.9, viscosity is dependent on temperature. For example, on a cold morning, the engine of a car turns over much more slowly when starting up as compared to on a warm day, when the engine starts up immediately. This is an effect due to the cold ambient temperature causing the oil to thicken or become more viscous. When the engine warms up, the lubricant thins out or becomes less viscous, thus reverting back to its original design viscosity at operating temperature. Many multigrade lubricants such as automobile oils are designed to work in both cold and hot conditions. The vast majority of industrial lubricants are single-grade oils and are therefore much less resilient to volatile ambient and operating temperatures. Currently, there is no uniform standard for measuring viscosity; however in the following sections, some of the popular techniques will be explored.

2.4 Viscosity Index

Viscosity index (VI) is the rate of change in viscosity due to the change in temperature for a given fluid. The higher the VI of an oil, the less of a tendency for the oil's viscosity to change with fluctuations in temperature. Synthetic oils tend to have a better VI than petroleum-based oils. If two oils are being considered and they have the same properties, then the one with the higher VI should be the oil of choice.

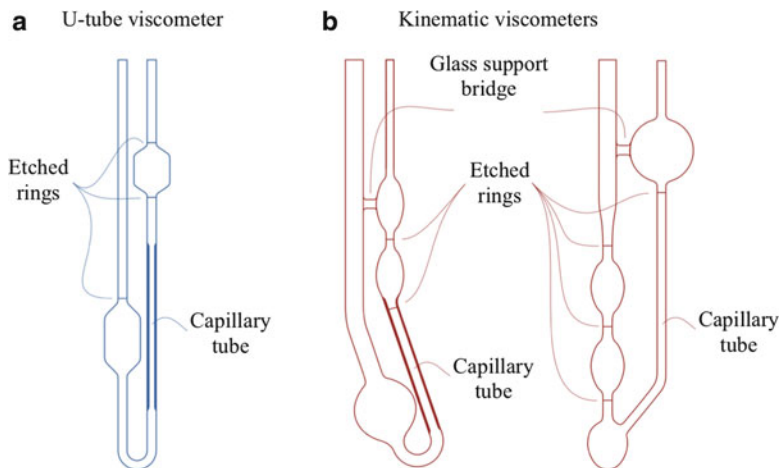


Fig. 10.10 Schematic of capillary viscometers: (a) British standard U-tube viscometer and (b) Ostwald kinematic viscometer [40]

2.5 Viscosity Measurement

The most commonly used apparatus in engineering applications for measuring viscosity is the capillary viscometer. Capillary viscometers are primarily used for measuring Newtonian lubricants with negligible end effects. Capillary viscometers are based on the principle that a specific volume of fluid will flow through a capillary and the time necessary for this volume of fluid to flow from one timing mark to another gives the kinematic viscosity. In these viscometers the fluid flow must be laminar to allow Poiseuille's law for steady viscous flow in a pipe to apply, allowing for the deduction of kinematic viscosity. Two of the more popular capillary viscometers are the British standard U-tube viscometer (Fig. 10.10a) and the Ostwald viscometer (Fig. 10.10b).

Capillary viscometers measure the kinematic viscosity of a fluid as defined by (10.7), which is derived from Poiseuille's law for steady viscous flow in a pipe:

$$v = \frac{\pi r^4 g l t}{8 L V} = k(t_2 - t_1) \quad (10.7)$$

where:

- v is the kinematic viscosity (m^2/s),
- r is the capillary radius (m),
- l is the mean hydrostatic head (m),
- g is the earth acceleration (m/s^2),
- L is the capillary length (m),
- V is the flow volume of the fluid (m^3),
- t is the flow time through the capillary, $t = (t_2 - t_1)$, (s),

k is the capillary constant which has to be determined experimentally by applying a reference fluid with a known viscosity or the manufacturer of the viscometer provides it.

2.6 Thermal Properties of Lubricants

Lubricants have three important thermal properties: specific heat, thermal conductivity, and thermal diffusivity. These parameters are important in evaluating the thermal effects during lubrication, such as the operating temperature of the surfaces and the cooling properties of the oil. The temperature characteristics are important in the selection process of a lubricant for a specific application. Other important thermal properties of a lubricant are pour point, cloud point, flash point, fire point, volatility and evaporation, oxidation and thermal stability, as well as surface tension. The temperature range over which a lubricant can be used is of extreme importance because at high temperatures, oils can decompose or degrade, while at low temperatures, oils may become solid or freeze. Oils can decompose by thermal and oxidative degradation. The decomposition of oil can cause a secondary effect where damage to the sensitive lubricated equipment may occur. A prime example of secondary damage is corrosion caused by the acidity of oxidized oils.

2.7 Pour Point

The pour point of a liquid is the lowest temperature at which it becomes semisolid and loses its flow characteristics. In order to determine the pour point, the oil is first heated to ensure solution of all ingredients. It is then cooled at a specific rate most commonly at decrements of 3 °C per minute; periodically, the container is tilted to check for any movement as illustrated in Fig. 10.11 [1]. The temperature 3 °C above the point at which the oil stops moving is recorded as the pour point. This property is important in the lubrication of any system exposed to low temperature, such as automotive engines, construction machines, military devices, and space applications, because it provides a lower bound for the operating temperature specification.

2.8 Cloud Point

The cloud point of a fluid is the temperature at which dissolved solids such as paraffin waxes are no longer soluble and begin to precipitate as a second phase giving the fluid a cloudy appearance during heating as shown in Fig. 10.12. The onset of a wax precipitation causes a distinct cloudiness or visible haze to appear in

Fig. 10.11 Illustration of a tilt check to verify if there is any movement for a lubricant during a pour test

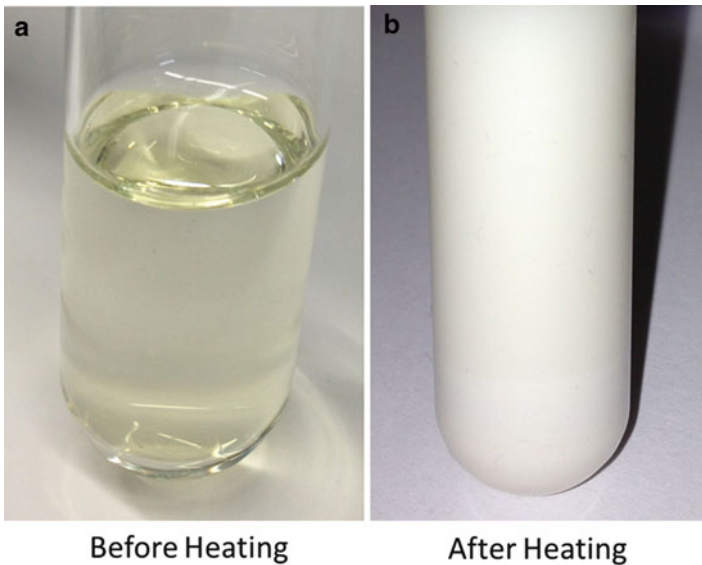


Fig. 10.12 Cloud point illustration of a transparent oil in a glass beaker: (a) before heating and (b) after heating

the beaker after heating. The cloud point has a practical application in capillary or wick feed lubrication systems in which the forming wax could potentially obstruct the oil flow. The cloud point is strictly limited to transparent fluids for the reason that measurement is based purely on observation through testing. If the cloud point of an oil is observed at a temperature higher than the pour point, the oil is said to have a “wax pour point.” On the contrary, if the pour point is reached without a cloud point, the oil is described as having a “viscosity pour point.”

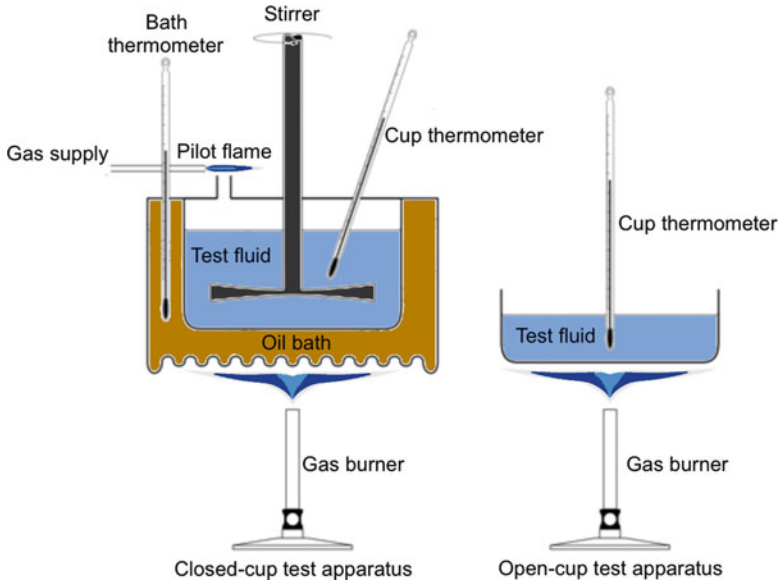


Fig. 10.13 Schematic diagram of the flash and fire point apparatus

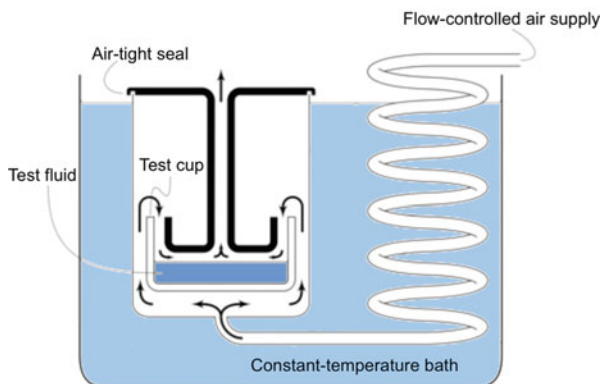
2.9 Flash and Fire Points

The only thermal properties, which define the fire hazard of a lubricant, are the flash and fire points. These properties are extremely important for safe application and use of a lubricant. The flash point of a lubricant is the temperature at which its vapor will flash ignite. Determination of the flash point requires oil to be heated at a standard pressure to a temperature high enough to produce sufficient vapor to form an ignitable mixture with air. Figure 10.13 illustrates two testing apparatuses: the closed-cup test and the open-cup test for measuring the flash and fire points. These tests work by heating a fluid and measuring its temperature at which the fluid's vapor is ignitable. The fire point of oil is the temperature at which enough vapor is produced to sustain burning after ignition. The fire point is always higher than the flash point. In general, the flash point and fire point of oils increase with increasing molecular weight. For a typical lubricating oil, the flash point is about 210 °C, whereas the fire point is about 230 °C [40].

2.10 Volatility and Evaporation

In many extended use or variable temperature applications, the loss of lubricant due to evaporation can be substantial. In particular, at elevated temperatures, oils may become more viscous and eventually dry out due to evaporation. The measure of

Fig. 10.14 Schematic diagram of an evaporation test apparatus



evaporation losses defines the volatility of a lubricant. In order to determine the lubricant volatility, a known quantity of lubricant is exposed in a vacuum thermal balance device. The evaporated material is then collected on a condensing surface and the decreasing weight of the original material is expressed as a function of time. Figure 10.14 shows an evaporation apparatus where a known quantity of oil is placed in a cup and aerated for a preset amount of time. The test cell is preheated to the required temperature in an oil bath. In this instrument, air enters through the periphery of the cup and flows across the surface of the oil and exits through the centrally located tube. At the completion of the test, the sample is cooled and weighed, revealing the percentage of lost mass, thus giving the evaporation rate. Recent advancements in lubricants have been through the use of ionic liquid lubricants for their composition of free flowing ions giving these fluids negligible vapor pressure and nonvolatility properties [43, 44].

2.11 Oxidation Stability

Oxidation stability is the resistance of a lubricant to molecular decomposition or reaction at elevated temperatures in an oxygen-enriched environment. Oxidation typically occurs in ambient environments where the air is composed of about 21 % oxygen. Lubricating oils rapidly oxidize when exposed to air at elevated temperatures, resulting in a strong impact on the useful life of an oil. Oxidation of oils is a complex process that includes thermally activated and physicochemical reactions that depend on the level of oil refinement, temperature, presence of metal catalysts, and operating conditions. Different compounds react at different temperatures and under different conditions [45, 46]. A lubricant that oxidizes rapidly requires more frequent maintenance or replacement resulting in higher operating costs.

Oils can be chemically modified to improve upon their oxidation stability by removing the hydrocarbon-type aromatics and molecules containing sulfur, oxygen, and nitrogen. More refined oils have a better oxidation stability; however, they have other shortcomings. Refined oils are typically more expensive to produce and they lead to a lubricant with poor boundary lubrication characteristics. For this reason, the oil selection for a particular application is always a compromise, depending on the type of job the oil is expected to perform. Blending antioxidant additives with oil can control oxidation. Details on antioxidants and the role of additives in lubricants will be discussed in a proceeding section.

2.12 Thermal Stability

All substances when heated above a certain temperature will naturally start to decompose, even if no oxygen is present. In this context, thermal stability is the resistance of a lubricant to molecular decomposition or reaction at elevated temperatures in the absence of oxygen. For example, when mineral oil is heated, it degrades to methane, ethane, and ethylene. Similarly, natural oils that are composed of fatty acids and esters have significant thermal instability due to the presence of double bonds in the unsaturated fatty acids. The presence of the double bonds in natural oils affects the thermal stability and causes the oil to breakdown at various temperatures into organic compounds, which adversely affect the functionality of the oil. Thermal stability of oils can often be improved through multiple types of refining processes such as epoxidation, metathesis, acylation, estolide formation, transesterification, and selective hydrogenation [47–60].

2.13 Surface Tension

Surface tension is a property of a liquid that allows it to resist an external force. Many lubricants show varying degrees of wettability and spreadability on surfaces. The wettability and spreadability characteristics of a lubricant are dependent on surface tension, which is especially sensitive to physicochemical changes. Depending on the degree of oxidation or the amount of additives present in a lubricant, the oils can have different wetting and spreading properties.

Surface and interfacial tension are related to the free energy of the surface and the attraction between the surface molecules, thus influencing the wetting and spreading characteristics. Surface tension refers to the free energy at a gas–liquid interface, while interfacial tension refers to interface between two immiscible liquids. A liquid with a large contact angle as shown in Fig. 10.15a has a high surface tension resulting in less physical spreading across the surface, thus acting as a poor lubricant. On the contrary, Fig. 10.15b illustrates a liquid with a small contact angle, having a low surface tension and thus spreading easily across the surface acting as a good

Fig. 10.15 Contact angle of a liquid droplet on a surface: (a) liquid with a large contact angle and (b) liquid with a small contact angle

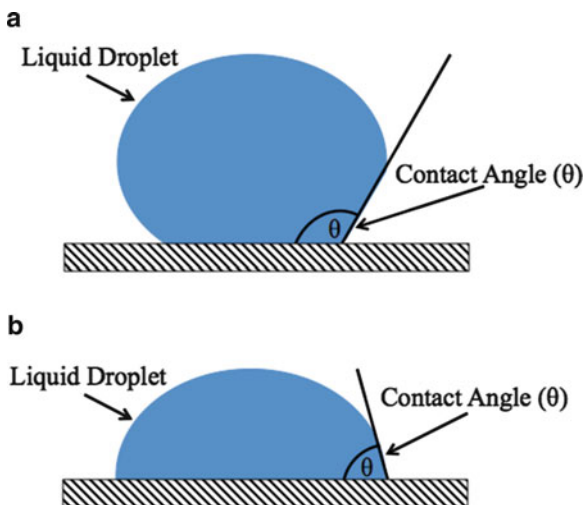


Table 10.1 Surface tension of various base oils [23]

Liquid	Surface tension (mN/m)
Water	72
Mineral oils	30–35
Esters	30–35
Methyl silicone	20–22
Perfluoropolyethers	19–21

lubricant. The surface tension of various base oils is presented in Table 10.1 [23]. As mentioned, surface tension for base oils is very sensitive to additives; for example, adding less than 0.1 % of methyl silicone to mineral oil reduces the surface tension by approximately 35 % to a value of about 21 mN/m.

3 Oil Additives

Base oils (vegetable oils, mineral oils, and synthetic oils) cannot always satisfy the demands of a high-performance lubricant by themselves [6]. For this reason, additives are blended with oils to enhance or modify the characteristics of a lubricant. Additives are synthetic chemical substances mixed with base oils to improve various characteristics of lubricants so the oils can placate the higher demand placed on them and satisfy specification requirements. Additives often improve existing properties, suppress undesirable properties, and introduce new properties to the base oils. One of the most important properties that additives enhance is a lubricant’s ability to form protective films, which is especially important in boundary lubrication conditions.

Additives are classified based on their behavior, which takes into consideration the portion of the tribological system that the additive influences. For this reason, additives can be classified into two categories [2]:

1. Additives that influence the physical and chemical properties of the base oils:
 - (a) Physical effects: e.g., viscosity–temperature characteristics, demulsibility, and low-temperature properties
 - (b) Chemical effects: e.g., oxidation stability
2. Additives that influence the characteristics of the metal surfaces by modifying their physicochemical properties: e.g., reduction of friction, increase of extreme pressure behavior, wear protection, and corrosion inhibition

The use of additives has a large influence on the performance of lubricants that make it possible to fulfill the increasing complex demands placed on lubricants. Nevertheless, there are some properties that cannot be influenced by additives, such as volatility, air release properties, thermal stability, thermal conductivity, compressibility, and boiling point. Many of these properties require chemical modifications through various refinement processes. When blending additives with base oils, it is important to have a well-balanced and optimized composition to improve the performance of the lubricant. This usually requires the formulation of high-performance base oils that are derived from highly refined oils and then mixed with additives to further enhance the lubricant's properties.

3.1 Additive Compatibility and Solubility

Individual additives are generally added to base oils in small amounts between 0.1 and 0.5 % [23] with about 10 % of the total lubricant composition consisting of additives. When using multiple additives in a lubricant, they should be compatible with each other and soluble in the lubricant. Mixing additives with each other or with base oils can result in synergistic or antagonistic effects. For this reason, there are some additives that are multifunctional products that decrease the incompatibility of additives that would adversely interfere with each other. Two or more additives in an oil are generally considered compatible (1) if they do not react with each other and (2) if their individual properties are advantageous to the functioning of the lubricant. Often, a normal practice is to consider a mixture of additives to be compatible if they do not give visible evidence of reacting together, such as a change in color or smell.

Additive solubility requires that additives must dissolve or form colloidal mixtures in their base oils without settling out. Figure 10.16 shows several base oils of various colors with additives. In this figure, the additives are dissolved into the base oil, so they cannot be seen. Often, when an additive settles out of the base oil, it renders that specific additive ineffective; therefore it is important for additives to remain dissolved or mixed over the entire useful life of the lubricant. Separation



Fig. 10.16 Colors of several base oils with additives

of an additive in storage or in service is extremely detrimental and can pose a hazard in some systems because the lubricant may not function properly. For example, elemental sulfur could be used as an additive in extreme temperature and pressure applications; however it is insoluble in oil, separating during storage and service, thus rendering it unusable as an additive in oil [40].

3.2 Lubricant Additives

Lubricant additives are usually organic or organometallic chemicals that are added to oils to improve the lubricating capacity and durability of the oil. Specific purposes of lubricant additives are to [1, 2]:

1. Enhance the wear and friction characteristics
2. Improve the oxidation resistance
3. Minimize corrosion
4. Control contamination by reaction products, wear particles, and other debris
5. Reduce excessive decrease of lubricant viscosity at high temperatures
6. Decrease the pour point
7. Inhibit the generation of foam

Carefully selected additives are extremely effective in improving the tribological performance of a lubricant. Most additive manufacturers maintain complete secrecy over the details of their products. A result of this secrecy is that the supplier and end user of the lubricant may only know that a particular lubricant contains a “bundle” of additives without knowing the composition of each additive. Larger businesses very often produce many different brands and types of lubricants, which are effectively the same or have similar properties and composition. In this way, they can formulate their own lubricant recipes and protect them as trade secrets. This type of secrecy surrounding additives means that their formulation and the

exact properties of a bundle is partly an art rather than a purely scientific or technical process. This allows each company in the lubrication industry to have their own unique competitive advantage. Many of the most common additive bundles used in lubricant formulations are antiwear additives, extreme pressure additives, oxidation inhibitors, corrosion inhibitors, detergents and dispersants, viscosity improvers, pour point depressants, and foam inhibitors. In some instances other additives like dyes and odor improvers are also added to the oils.

3.2.1 Wear and Friction Improvers

Additives, which improve wear and friction properties, are the most important additives used in lubricant formulations. In machinery, when two surfaces engage in metal-to-metal contact and begin to move relative to each other, hydrodynamic lubrication does not occur at the onset or in the case of severe stress; hence, the lubricating system runs in the boundary or mixed lubrication regime. In this case, wear and friction improvers are necessary in any metalworking fluid, engine oil, hydraulic fluid, or lubricating grease to prevent welding of the moving parts, reduce wear, and lower friction. Wear and friction improvers consist of chemical additives that can be divided into three groups: adsorption or boundary additives, antiwear (AW) additives, and extreme pressure (EP) additives. “Boundary” additives are friction and wear modifiers such as fatty acids that are added to oil to minimize the asperity contact. The term “antiwear” commonly refers to wear reduction at moderate loads and temperatures whereas the term “extreme pressure” refers to high loads and temperatures. All of these additives control the lubricating performance of the oil, making their usage very important. If oil lacks its lubricating ability, excessive wear and friction will result, causing damage to the moving parts with usually an increase in energy consumption.

3.2.2 Adsorption or Boundary Additives

Adsorption or boundary additives, also known as “friction modifiers,” control the adsorption type of lubrication and are often used to prevent stick-slip phenomena [61]. Adsorption additives are vital in boundary lubrication. The additives currently used are mostly fatty acids, esters, and amines of the fatty acids. These types of additives generally consist of a polar carboxyl group ($-\text{OH}$) at one end of the molecule that reacts with the contacting surfaces through an adsorption (adherence) mechanism to form a surface film as shown in Fig. 10.17. The molecules attach to the charged surface by the polar group to form a layer of molecules, which reduces friction and wear by having low interfacial shear stress and minimized asperity contact. The surface films or monolayers produced are only effective in boundary lubrication at relatively low temperatures and low loads.

The important characteristic of these additives is their molecular structure consisting of an unbranched chain of carbon atoms with sufficient length to ensure

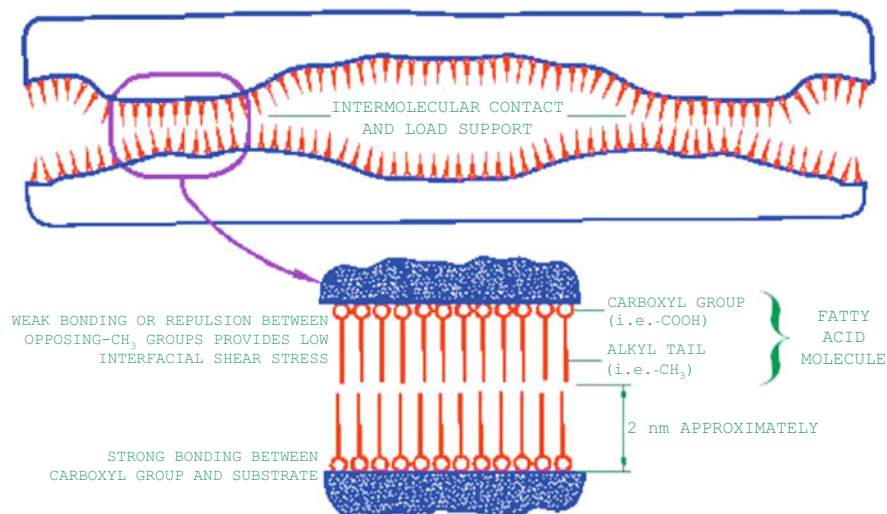


Fig. 10.17 Adsorbed molecules on a surface forming a monolayer

a stable and durable film that allows for the formation of close-packed monolayers. In natural oils, these molecules are generally unsaturated fatty acids have chain lengths of 18 or 16 carbon atoms consisting of oleic, linoleic, stearic, and palmitic acids [6]. In some specialized lubricants, unique additives are utilized which combine adsorption or boundary properties with corrosion protection or some other property for a specific application [61]. Depending on the type of additive used, adsorption additives are highly sensitive to the effects of temperature and can lose their effectiveness at temperatures between 80 and 150 °C. With increased temperature, these additives can reach a critical temperature threshold where the energy input to the surface is high enough to cause the additive to desorb rendering it inept. This critical temperature can be controlled by changing the additive's concentration, where a higher concentration results in a higher critical temperature. However, there is a downside to using a higher concentration as it also causes the lubricant to be more expensive; thus for specific applications, it is important to compare lubricant performance with cost.

3.2.3 Antiwear Additives

Antiwear (AW) additives are used when moderate stress is experienced between two surfaces in contact. In order to protect contacting surfaces at moderate loads and temperatures, antiwear additives are used. These additives function through chemisorption reactions with metal surfaces to form tribochemical reaction layers, which are protective surface layers that are much more durable than the adsorption monolayers. There are several different types of antiwear additives that are

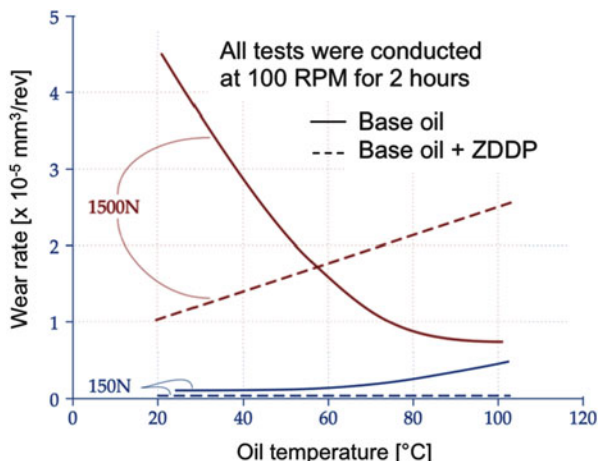
currently used in oil formulations typically in concentrations of 1–3 % by weight. The vast majority of antiwear additive are based on organic phosphorus compound such as diethylphosphate, dibutylphosphate, and tributylphosphate [2]. In engine oils, the most commonly used antiwear additive is zinc dialkyldithiophosphate (ZDDP), and in gas turbine oils, tricresylphosphate or other phosphate esters are used.

3.2.4 Extreme Pressure Additives

Extreme pressure (EP) compounds are designed to react with metal surfaces under extreme conditions of high load and temperature to prevent welding of the moving parts that would otherwise cause severe damage. Similar to antiwear additives, extreme pressure additives form layers on the metal surface by adsorption or chemisorption due to their polar molecules. Usually EP additives contain at least one aggressive nonmetal, such as sulfur, antimony, iodine, or chlorine molecules [40]. When hydrodynamic lubricating films are not present and a system runs under boundary lubrication, this can result in increased operating temperatures where exposed metal surfaces can become hot. The increase in temperature allows for EP additives to react with the warm metal surface forming tribochemical reaction layers composed of iron phosphides, sulfides, sulfates, oxides, and carbides that prevent direct contact between the sliding metals [2]. These reactions are designed to create protective low shear strength surface films that reduce friction and wear.

The use of EP additives results in a mild form of corrosion due to the reaction with the metallic surfaces; for this reason, the additive concentration is an important parameter. For example, if the EP additive concentration is too high, then excessive corrosion may occur resulting in increased wear. On the contrary, if the EP additive concentration is too low, then the surfaces may not be fully protected and failure could result. In some instances, EP additives contain sulfur or phosphorus, which is useful in suppressing oil oxidation; however, decomposition of these additives has been known to occur at even moderate temperatures. Therefore, EP additives containing sulfur or phosphorus are not recommended to extend the lubricant useful lifetime at high temperatures. There are several different types of EP additives currently used in oils, many of which are not considered toxic or carcinogenic. The most commonly used EP additives are dibenzylsulfide, trichloroacetane and chlorinated paraffin, chlorinated wax, chlorinated paraffinic oils, and molybdenum disulfide [2, 10]. Dibenzylsulfide is a mild EP additive with minimal reactivity and corrosion. Trichloroacetane and chlorinated paraffin are severe EP additives resulting in excessive corrosion, particularly in the presence of water. Molybdenum disulfide is a well-known solid lubricant that provides lubrication in extreme temperatures and contact pressures. It functions by depositing a solid lubricant layer on the contacting surfaces minimizing the potential surface contact. Molybdenum disulfide is noncorrosive, thus making it a popular additive despite being highly sensitive to humidity, which causes it to decompose.

Fig. 10.18 The influence of load and oil temperature on wear rate for base oil and base oil containing ZDDP at 150 N and 1,500 N



3.2.5 Zinc Dialkyldithiophosphate (ZDDP)

ZDDP is a well-known and commonly used antiwear additive primarily used in automotive lubricants. It was originally developed as an antioxidant and detergent, but was later revealed to exhibit superior antiwear properties and function as a mild EP additive [2]. By modifying the molecular structure, ZDDP derivatives can be produced such as zinc diphenyldithiophosphate; however many of these new compounds are less effective as ZDDP in reducing wear and friction. The presence of zinc in ZDDP plays an important role in minimizing the wear rate. The absence of zinc or replacing zinc with another metal substitute leads to an increase in wear rate. Experimental results indicate that ZDDP derivatives containing zinc alternatives have a higher wear rate in the following order: cadmium, zinc, nickel, iron, silver, lead, tin, antimony, and bismuth [62]. Cadmium offers the lowest wear rates but is too toxic for practical applications, making zinc the best alternative. Figure 10.18 shows the influence of load and temperature on wear rate for both base oil and a base oil containing ZDDP [63]. It can be seen that the wear rates increase with increasing temperature at a loads of 1,500 N for base oils containing ZDDP, but at low loads of 150 N, temperature has no effect on base oils containing ZDDP. For pure base oil, the trends are reversed. This figure demonstrates how ZDDP is most suitable for moderate loads with lower temperatures. For this reason, ZDDP is often used in valve trains of internal combustion engines to reduce friction and wear [64].

3.2.6 Tricresylphosphate

Tricresylphosphate (TCP) functions similar to ZDDP through chemisorption. It is a very effective antiwear additive that reduces wear and friction at temperatures up to approximately 200 °C. Beyond this temperature, TCP additives reach their critical

temperature threshold where the energy input to the surface causes the chemisorbed films to desorb. Desorption causes the additive to form less effective, much weaker, thick phosphate films with limited load-carrying capacity, resulting in high friction and wear [65, 66].

3.2.7 Antioxidants

Many of today's lubricants contain antioxidant additives to delay or minimize the onset of oxidation. Antioxidants or oxygen inhibitors are either natural or artificial additives that have the ability to suppress oxidation [67]. Natural antioxidants such as sulfur or nitrogen compounds can be naturally found in mineral oils. These compounds function by scavenging the radicals produced during the oxidation process. Phosphorus-based organic compounds found in extreme pressure and antiwear additives have been shown to function as artificial antioxidants [68]. Other common antioxidant additives are ZDDP, metal deactivators, and simple hydrocarbons such as phenol derivatives, amines, and organic phosphates [69–75]. Antioxidants are typically added to lubricants in quantities of approximately 1 % by weight.

Lubricants naturally oxidize or age during service. General characteristics of aged lubricants are discoloration and a burnt odor [76, 77]. Oxidation inhibitors prevent oxygen from attacking the base oils, thereby stabilizing the lubricant's viscosity and other properties [75, 78, 79]. This in turn prevents organic acid buildup that can cause corrosion. Antioxidants as their name suggests minimize the rate of oxidation occurring within a lubricant. This in turn improves the lifetime of the lubricant, resulting in significant decreases in friction and wear, which can lead to improved performance of machinery [69, 70, 74, 80, 81]. The main effect of oxidation is a gradual rise in the viscosity and acidity of a lubricant as shown in Fig. 10.19, which shows the variation of viscosity and acidity of a mineral oil as a function of oxidation time [82]. Both viscosity and acidity reach a critical oxidation time at approximately 120 h and 80 h, respectively, where their values increase tremendously. Beyond these durations, the oils have become extremely rancid through oxidation and should be replaced immediately.

A highly oxidized oil should be replaced promptly, since it can cause power losses due to increased viscous drag and difficulties in pumping of the oil through lubricant feed lines. It is important to realize that increases in viscosity are not only caused by oxidation but also by foreign contaminants entering the lubricant such as diesel soot. High levels of oil acidity can be problematic due to concerns of corrosion of vulnerable components such as lead, copper, and cadmium bearings.

3.2.8 Corrosion Control Additives

Corrosion control additives are classified as corrosion inhibitors and rust inhibitors. Corrosion inhibitors are used to protect nonferrous metal (i.e., copper, aluminum, tin, cadmium) surfaces against potential corrosive agents in the lubricant [83].

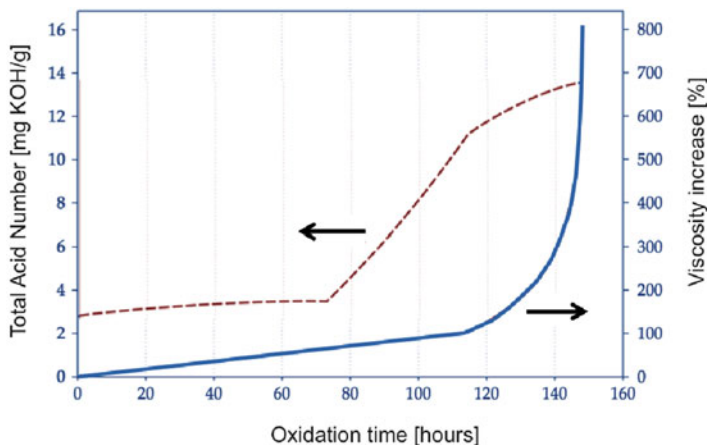
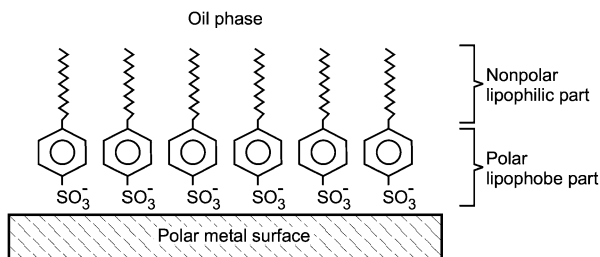


Fig. 10.19 The effect of oxidation times on viscosity and acidity for a typical base oil [40, 82]

Fig. 10.20 Function of corrosion control additives on a polar metal surface [2]



Rust inhibitors are used to protect ferrous metal (i.e., steel, iron, and iron alloys) surfaces against corrosion. The mechanism behind corrosion control additives is quite simple. Anticorrosion additives are molecules with long alkyl chains and polar groups that can be adsorbed on the metal surface forming densely packed, hydrophobic layers as shown in Fig. 10.20 [2]. The adsorption mechanism is based on either physical or chemical interaction of the polar anticorrosion additive with the metal surface [84]. However, due to the relatively high surface activity, anticorrosion additives compete with other polar additives such as EP and AW additives for the metal surface and can therefore reduce their efficiency. For this reason, it is important to use highly efficient and highly polar anticorrosion additives.

Corrosion Inhibitors

Corrosion inhibitors are used to protect the nonferrous surfaces of bearings, seals, and other vulnerable components against corrosive attacks by various additives. Highly corrosive additives generally contain sulfur, phosphorus, iodine, chlorine,

and oxidation by-products [84]. Corrosion inhibitors can be classified into three categories: film-forming compounds, complex-forming chelating agents, and sulfur scavengers [2]. The function of film-forming corrosion inhibitors consists of building protective layers on the nonferrous metal surface, thus preventing the surface reaction of metal ions that would work as prooxidants (chemicals that induce oxidation). Complex-forming chelating agents are able to build oil-soluble molecules with significantly reduced catalytic activity that have minimal influence on the nonferrous metal ions that would ordinarily oxidize the lubricant. Sulfur scavengers are corrosion inhibitors that are able to catch corrosive sulfur molecules by integrating sulfur into their molecular structure.

Corrosion attacks on nonferrous metallic parts can occur through a variety of mechanisms such as the presence of corrosive contaminants, oxidation by-products, and water present in the lubricant. Additionally, high-temperature effects can also instigate corrosion. Through the three types of corrosion inhibitors, many of the pro-corrosion products can be neutralized before they cause any damage to the operating parts of the machinery or to the lubricant. Commonly used corrosion inhibitors that operate through film-forming compound are benzotriazole, tolyltriazole, ZDDP, and trialkylphosphites. Complex-forming chelating agents can consist of *N,N*-disalicylidenealkylendiamines and sulfur scavengers can consist of 2,5-dimercapto-1,3,4-thiadiazole where sulfur is captured in the alkyl-sulfur-thiadiazol bonds.

Rust Inhibitors

Rust inhibitors are used to protect ferrous metal surfaces. Rust, the visible trace of corrosion, is often generated by the presence of dissolved oxygen or water in a lubricant. These contaminants in the lubricant can cause electrolytic attacks on the metal surfaces. These attacks can become severe and prevalent with increases in temperature. Rust inhibitors usually consist of long chain alkylarylsulfonic acids that can be neutralized with lyes. These compounds are typically known as petroleum sulfonates or mahogany sulfonates which are by-products from the production of white oils with oleum [2]. Rust inhibitors function by attaching themselves to the surface (see Fig. 10.21), severely reducing the mobility of water and thus minimizing the amount of corrosion that can occur [84]. Metal sulfonates, amine succinates, and other polar organic acids are additives used to control the corrosion of ferrous metals. The calcium and barium sulfonates are suitable for more severe conditions of corrosion, whereas the succinates and the other organic acids are used when corrosion is moderate. Low molecular weight sodium sulfonates have anticorrosion properties in water-based metalworking fluids, engine oils, and rust preventatives. High molecular weight sulfonates distinguish themselves as highly efficient corrosion inhibitors especially when used for divalent cations like calcium, magnesium, and barium. The use of the barium compounds has begun to decrease due to toxicological and environmental concerns.

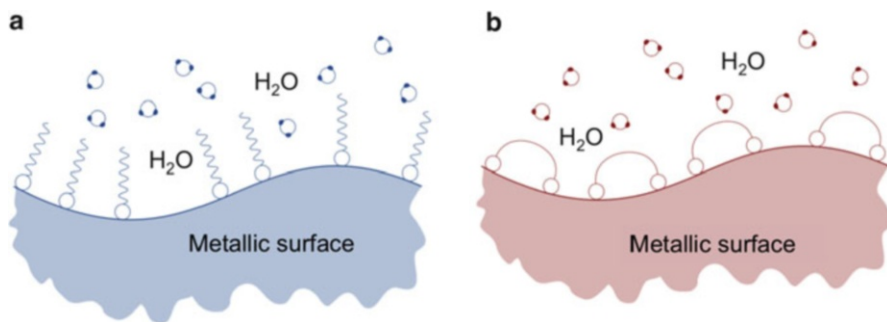


Fig. 10.21 Function of rust inhibitors on a metallic surface: (a) rust inhibitors as they first attach to the surface and (b) rust inhibitors after forming a protective layer

3.2.9 Detergents and Dispersants

Engine oils and other lubricants are repeatedly exposed to other functional fluids through leakage, combustion by-products, and other contaminants throughout their lifetime. Water adversely affects many lubricants because it aids in oxidation and can form an oil–water emulsion. When sulfur is present in the fuel during the combustion process, this causes the formation of sulfurous or sulfuric acid. These sulfur-based compounds can then be dissolved by water resulting in corrosion of the engine. Lubricants can face a multitude of contaminants such as wear debris, unburned fuel, by-products of the base oil, corrosion products, dust from the atmosphere, water, and other lubricants [40]. These contaminants deplete the lubricant by reducing its lubricating capacity and making the lubricant more corrosive, thus rendering it ineffective. The agglomeration of particles in engine oils, for instance, can cause oil supply pipelines or filters to become clogged and blocked, resulting in a very destructive situation for an engine. To minimize and help prevent these adverse effects, additives known as “detergents” and “dispersants” are used [85]. Detergents and dispersants are materials that chemically react with oxidation products and enable the oil to suspend dirt particles and debris, which can be removed through filtration [1]. They also help to neutralize acid buildup. The primary functions of these additives are to (1) neutralize any acids formed during the burning of fuel, (2) prevent varnish formation and corrosion on the operating parts of the engine, and (3) prevent the flocculation or agglomeration of particles and carbon deposits which may clog the oil flow path [40]. Table 10.2 presents some of the properties of commonly used dispersants.

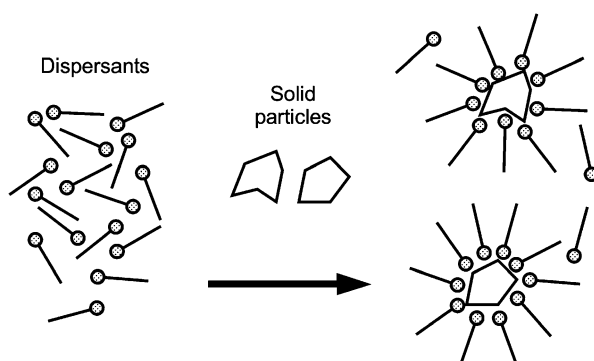
Detergents and dispersant (DD) additives usually consist of molecules having a large oleophilic hydrocarbon tail and a polar hydrophilic head. The tail section acts as a solubilizer in the base oil, while the head is attracted to contaminants in the lubricant. DD additives work by having multiple dispersant molecules attach to a single solid contaminant forming micelles whereby the nonpolar tail prevents

Table 10.2 Properties of commonly used dispersants [40]

Dispersant	Lacquer and varnish prevention	Acid neutralization	Coagulation prevention
Dispersants and over-based dispersants			
Calcium, barium, or zinc salts of sulfonic, phenol, or salicylic acid	Good, especially at high temperatures	Good	Fair
Carboxylic and salicylic type additives	Good	Fair	Poor (they can cause coagulation)
Mild dispersants (i.e., ashless compounds)			
Low-weight polymers of methacrylate esters or long chain alcohols	Fair ^a	Weak	Good
Polar vinyl compounds	Fair ^a	Weak	Good
Amines (e.g., triethylene amine)	Fair ^a	Fair	Good
Saturated succinimide	Fair ^a	Weak	Good

^aThese additives are only effective at low temperature

Fig. 10.22 Function of dispersants undergoing the peptization process [2]



adhesion of the polar soot particle on the metal surfaces as well as the agglomeration into larger particles as illustrated in Fig. 10.22 [2]. The process of DD additives attaching to colloid particles in the oil is known as peptization.

3.2.10 Viscosity Improvers

Additives that prevent the decrease in oil viscosity with temperature are known as viscosity index improvers. Viscosity index improvers are additives that consist of high molecular weight polymers, which are dissolved in the oil [86]. These molecules are chain-like molecules whose solubility depends on chain length, structure, and chemical composition [87]. Generally, the base oil solubility of these polymer chains deteriorates as the temperature falls and improves with increasing temperature so as to maintain the viscosity of the base oil. Due to the poor solubility at low temperatures, the chain-like viscosity improver molecules

Table 10.3 Types of polymeric viscosity modifiers and their most widely used applications [2]

VM type	Description	Main applications
OCP	Olefin copolymers	Engine and hydraulic oils
PAMA	Polyalkyl(meth)acrylates	Gear and hydraulic oils
PIB	Polyisobutylene	Gear oils, raw material for ashless dispersants
SIP	Hydrogenated styrene–isoprene copolymers	Engine oils
SBR	Hydrogenated styrene–butadiene	Engine oils

form coils of small volume, and as the temperature is increased, these molecules expand and unravel, resulting in an increasing beneficial effect on high-temperature viscosity [88]. The increase in viscosity and viscosity index depends on the polymer type, the molecular weight, and the concentration of viscosity improvers in the lubricant [89]. Depending on the projected application, molecular weights of the viscosity improver additives can range significantly. For example, viscosity index improvers such as polyalkylmethacrylates (PAMAs) can have molecular weights between 15,000 and 250,000 g/mol and polyisobutylene (PIBs) can have molecular weights between 2,000 and 5,000 g/mol. Some of the more commonly used viscosity improvers have found favor for certain applications. Table 10.3 shows the most important viscosity modifiers and their main applications. It can be seen that many viscosity modifiers find their use in engines followed by hydraulic and gear oils. Concentrations of viscosity improver additives are usually between 3 and 30 % mass fraction. As a result of their high molecular weight, viscosity modifiers are always dissolved in the base oil. Figure 10.23 describes various viscosity index improvers by polymer type, chain structure, and monomer makeup [2].

3.2.11 Pour Point Depressants

Pour point depressants (PPD) are similar to viscosity improvers. They help to keep the oil thin at low temperatures by preventing the generation of wax crystals. The major difference between the polymers used in viscosity improvers and PPD is their application concentration and the selection of monomer compounds [2, 90]. The molecular weight and thickening efficiency of PPDs are minor compared to that of viscosity improvers with mass fraction percentages that vary from 0.1 % to a




Polymer type	General structure	Chemical type
Homopolymer	A-A-A-A-A-A-A-A-A	PIB, PAO
Random	A-B-A-B-B-A-B-A-A-B	PMA, OCP
Alternating	A-B-A-B-A-B-A-B-A-B	MSC (Maleate Styrene Copolymer)
Random Block	A-A-A-B-B-A-A-B-B-B	SBR, SIP, OCP
Biblock (A-B block)	A-A-A-A-A-B-B-B-B-B 	SIP
Tapered Block		SBR
Graft copolymers	A-B-A-B-B-A-B-A-A-B X X	OCP-g-PMA or SBR-g-PMA
Star polymers		SBR, OCP

Fig. 10.23 Viscosity index improvers, chain structures, and monomer makeup [2]

maximum of 2 %. Generally, additional thickening effects occur, but are usually limited by solubility thresholds within the base oils.

3.2.12 Foam Inhibitors

The foaming of lubricants is a very undesirable effect that can cause increased oxidation by the intensive mixture with air, cavitation damage, and insufficient oil transport in circulatory lubrication systems that can cause lubrication starvation. Despite the negative mechanical influences, the foaming tendency is dependent on the lubricant itself and is influenced by the surface tension of the base oil and by the presence of surface-active substances such as detergents, corrosion inhibitors, and other ionic compounds. When describing the characteristics of lubricant foaming, there are two types: surface foam and the inner foam.

Surface foam refers to the foam at the surface of the lubricant that is usually visibly noticeable. This foam can be controlled by foam-inhibiting additives. Effective inhibitors possess a lower surface tension compared to the lubricant base oil, which are usually not soluble in the base oil, and therefore have to be finely dispersed in order to be sufficiently stable even after long-term storage or use. The particle size of the dispersed foam inhibitors for surface foam should be smaller than 100 μm . For enhanced performance, the particle size should be smaller than 10 μm [91].

The less innocuous inner foam refers to finely dispersed air bubbles within the lubricant that can form stable dispersions. Unfortunately, the vast majority of foam inhibitors used to control the surface foam tend to stabilize the inner foam dispersion. This makes the problem of removing the inner foam a challenge. On the

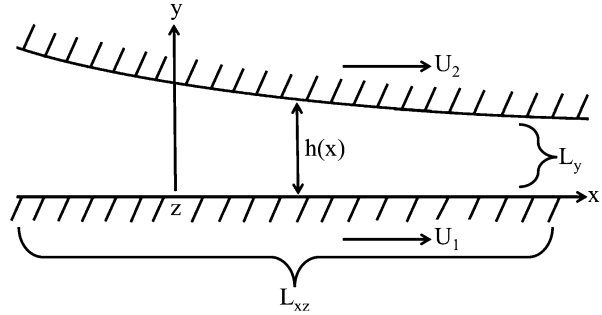
contrary, many of the additives used in lubricants have a negative influence on the inner foam stability thereby inadvertently minimizing the presence of the air bubbles [2]. Additives cannot improve lubricants that need excellent air release properties. Lubricants that need excellent air release properties operate as turbine oils which have to be formulated using specially selected base oils and additives. Air is not only present in the lubricants in the form of dispersed air bubbles as in surface and inner foam, but air can also be physically dissolved in the oil up to about 9 % volume fraction of the base oil. This type of air can cause severe problems like cavitation and cannot be controlled by additives.

The purpose of foam inhibitors is to destabilize foam generated during the lubricants operating cycle. Usually long chain silicone polymers are used in very small quantities of about 0.05–0.5 % by weight. Liquid silicones, such as linear and cyclic polydimethylsiloxanes, are very efficient antifoam additives at low concentrations. Silicone foam inhibitors are pre-dissolved in aromatic solvents to ensure stable dispersions when in use. When compared to other additives, silicone foam inhibitors have the disadvantage of settling out of the lubricant due to their insolubility and their strong affinity to polar metal surfaces. Recently, silicone-free foam inhibitors have been developed. These additives are being used extensively in metalworking processes as cutting fluids as well as hydraulic fluids. Silicone-free foam inhibitors consist of poly(ethylene glycols) (polyethers), polymethacrylates, tributylphosphate, and miscellaneous organic copolymers [2].

4 Fundamental Equations

This section discusses the basic equations that govern the application and science of lubricants and lubrication. In particular incompressible fluids will be assessed. The equations that describe lubrication with continuous fluid films are derived from the fundamental equations of fluid dynamics through specified geometry of the typical lubricant film as illustrated in Fig. 10.24 [7]. In the presented examples, lubricant films are described by their small thickness relative to their lateral size described as the “plane” of the film, as they would be in true application. In the derivations, L_y and L_{xz} denote the characteristic dimensions across the film thickness and the plane of the film, respectively, as indicated in Fig. 10.24. Typical industrial bearings experiencing liquid lubrication are characterized by $(L_y/L_{xz}) = O(10^{-3})$. This fact alone, and the assumption of laminar flow, permits the combination of the equations of motion and continuity into a single equation in lubricant pressure, revealing the infamous Reynolds equation. Much of the theory of lubrication is concerned with the solution of the Reynolds equation and in some instances the added solution of the equation of energy, under specified lubricating conditions. When surfaces are deformable, for example, in human and animal joints or rolling contact bearings, the equations of elasticity and the pressure dependence of lubricant viscosity must be included in the solution of a lubrication problem.

Fig. 10.24 Schematic of lubricant film



4.1 Equations of Motion

The basic equations that govern fluid flow of a lubricant begin with the Navier–Stokes equation [92], for an incompressible, constant viscosity fluid having a density ρ , velocity v , pressure p , viscosity μ , and body force f described in (10.8) [93]:

$$\rho \left[\frac{\partial v}{\partial t} + (v \cdot \nabla v) \right] = -\nabla p + \mu \nabla^2 v + \rho f \tag{10.8}$$

The corresponding equation of continuity for a constant density, incompressible fluid is as follows:

$$\text{div } v = 0 \tag{10.9}$$

These equations can be nondimensionalized by normalizing the orthogonal Cartesian coordinates (x,y,z) with the corresponding length scales and the velocities with the appropriate velocity scales, U^* in the x - z plane and V^* perpendicular to it [7]:

$$\text{Normalized } x, y, z \text{ terms : } x = L_{xz}\bar{x}, y = L_y\bar{y}, \text{ and } z = L_{xz}\bar{z} \tag{10.10a}$$

$$\text{Normalized velocity terms : } u = U^*\bar{u}, v = V^*\bar{v}, \text{ and } w = U^*\bar{w} \tag{10.10b}$$

It should be noted that the characteristic velocity in the y -direction V^* cannot be chosen independent of U^* , as the equation of continuity must always be satisfied. Substitution of (10.10a and 10.10b) into (10.9) yields

$$\frac{\partial \bar{u}}{\partial \bar{x}} + \frac{V^*L_{xz}}{U^*L_y} \frac{\partial \bar{v}}{\partial \bar{y}} + \frac{\partial \bar{w}}{\partial \bar{z}} = 0 \tag{10.11}$$

revealing that the terms of the equation of continuity are satisfied provided that

$$\frac{V^*L_{xz}}{U^*L_y} = O(1) \text{ or } V^* = \left(\frac{L_y}{L_{xz}} \right) U^* \tag{10.12}$$

From (10.12), the velocity scale in the y-direction has been established. The next step is to nondimensionalize the pressure and time terms [7]:

$$\text{Normalized pressure term : } \bar{p} = r_e \frac{P}{\rho U^{*2}} \quad (10.13a)$$

$$\text{Normalized time term : } \bar{t} = \Omega t \quad (10.13b)$$

In (10.13a), the reduced Reynolds number, r_e , and in (10.13b), the nondimensional frequency, $\bar{\Omega}$, are defined as

$$\text{Reduced Reynolds number : } r_e = \left(\frac{L_y}{L_{xz}} \right) \frac{L_y U^*}{\nu} \quad (10.13c)$$

$$\text{Nondimensional frequency : } \bar{\Omega} = \left(\frac{L_y}{L_{xz}} \right) \frac{L_y (L_{xz} \Omega)}{\nu} \quad (10.13d)$$

In (10.13b) and in (10.13d), Ω is the characteristic frequency of the system. For example, in journal bearings, the characteristic frequency is related to the rotational velocity of the journal. Taking the shaft surface velocity as the characteristic velocity, $U^* = R\omega$, and the journal radius as the characteristic length in the plane of the bearing, then $L_{xz} = R$, resulting in $r_e \approx \bar{\Omega}$. Making use of this approximation and substituting (10.10a), (10.10b) and (10.13a), (10.13b) into (10.8), the equations of motion and continuity can be rewritten in terms of the normalized quantities as follows:

$$r_e \left(\frac{\partial \bar{u}}{\partial \bar{t}} + \bar{u} \frac{\partial \bar{u}}{\partial \bar{x}} + \bar{v} \frac{\partial \bar{u}}{\partial \bar{y}} + \bar{w} \frac{\partial \bar{u}}{\partial \bar{z}} \right) = - \frac{\partial \bar{p}}{\partial \bar{x}} + \frac{\partial^2 \bar{u}}{\partial \bar{y}^2} + \left(\frac{L_y}{L_{xz}} \right)^2 \left(\frac{\partial^2 \bar{u}}{\partial \bar{x}^2} + \frac{\partial^2 \bar{u}}{\partial \bar{z}^2} \right) \quad (10.14a)$$

$$\left(\frac{L_y}{L_{xz}} \right)^2 \left[r_e \left(\frac{\partial \bar{v}}{\partial \bar{t}} + \bar{u} \frac{\partial \bar{v}}{\partial \bar{x}} + \bar{v} \frac{\partial \bar{v}}{\partial \bar{y}} + \bar{w} \frac{\partial \bar{v}}{\partial \bar{z}} \right) - \frac{\partial^2 \bar{v}}{\partial \bar{y}^2} - \left(\frac{L_y}{L_{xz}} \right)^2 \left(\frac{\partial^2 \bar{v}}{\partial \bar{x}^2} + \frac{\partial^2 \bar{v}}{\partial \bar{z}^2} \right) \right] = - \frac{\partial \bar{p}}{\partial \bar{y}} \quad (10.14b)$$

$$r_e \left(\frac{\partial \bar{w}}{\partial \bar{t}} + \bar{u} \frac{\partial \bar{w}}{\partial \bar{x}} + \bar{v} \frac{\partial \bar{w}}{\partial \bar{y}} + \bar{w} \frac{\partial \bar{w}}{\partial \bar{z}} \right) = - \frac{\partial \bar{p}}{\partial \bar{z}} + \frac{\partial^2 \bar{w}}{\partial \bar{y}^2} + \left(\frac{L_y}{L_{xz}} \right)^2 \left(\frac{\partial^2 \bar{w}}{\partial \bar{x}^2} + \frac{\partial^2 \bar{w}}{\partial \bar{z}^2} \right) \quad (10.14c)$$

$$\frac{\partial \bar{u}}{\partial \bar{x}} + \frac{\partial \bar{v}}{\partial \bar{y}} + \frac{\partial \bar{w}}{\partial \bar{z}} = 0 \quad (10.15)$$

4.2 Lubrication Approximations of Bearings

The normalization of (10.10a), (10.10b) and (10.13a), (10.13b) illustrates that each of the variable terms in 10.14a, 10.14b, 10.14c, and (10.15) is of the same order, e.g., $O(1)$. However, this indicates that the relative importance of the variable terms

is affected only by the magnitude of the dimensionless parameters $\left(\frac{L_y}{L_{xz}}\right)$ and r_e . In true applications, lubricant films are significantly thin relative to their lateral size. In a liquid lubricated bearing the $\left(\frac{L_y}{L_{xz}}\right)$ ratio can be on the order of 10^{-3} and for gas bearings a film thickness of $h \approx 2.5 \mu\text{m}$ is not unusual. The lubrication approximation of the Reynolds equation is established with the assumption that $\left(\frac{L_y}{L_{xz}}\right) \rightarrow 0$ and that $r_e \rightarrow 0$. Under these conditions, (10.14a, 10.14b, and 10.14c) indicate that

$$\frac{\partial \bar{p}}{\partial \bar{y}} = O(10^{-6}) \quad \text{and that} \quad \frac{\partial \bar{p}}{\partial \bar{x}} \approx \frac{\partial \bar{p}}{\partial \bar{z}} = O(1) \quad (10.16)$$

yielding new versions of (10.14a, 10.14b, and 10.14c) and (10.15), written in terms of the fundamental variables for a bearing

$$\frac{\partial p}{\partial x} = \mu \frac{\partial^2 u}{\partial y^2}, \quad \frac{\partial p}{\partial y} = 0, \quad \text{and} \quad \frac{\partial p}{\partial z} = \mu \frac{\partial^2 w}{\partial y^2} \quad (10.17)$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \quad (10.18)$$

4.3 The Reynolds Equation

Derivation of the Reynolds equation begins by first examining (10.17). Here, the pressure gradient in the y-direction, i.e., across the film, is zero, leaving only the pressure gradients in the x- and z-directions to be integrated to obtain

$$u = \frac{1}{2\mu} \frac{\partial p}{\partial x} y^2 A y + B \quad (10.19a)$$

$$w = \frac{1}{2\mu} \frac{\partial p}{\partial z} y^2 C y + D \quad (10.19b)$$

In (10.12), the integration constants A, B, C, and D can be solved using the boundary conditions for velocity from Fig. 10.24, where

$$u = U_1 \quad \text{and} \quad w = 0 \quad \text{at} \quad y = 0 \quad (10.20a)$$

$$u = U_2, \quad \text{and} \quad w = 0 \quad \text{at} \quad y = h \quad (10.20b)$$

Integration of (10.19a and 10.19b) with the conditions in (10.20a and 10.20b) yields the velocity components in the x- and z-planes of the bearing

$$u = \frac{1}{2\mu} \frac{\partial p}{\partial x} (y^2 - yh) + \left(1 - \frac{y}{h}\right) U_1 + \frac{y}{h} U_2 \quad (10.21a)$$

$$w = \frac{1}{2\mu} \frac{\partial p}{\partial x} (y^2 - yh) \quad (10.21b)$$

Equation (10.21a and 10.21b) reveals a pressure distribution that is not subjective. In fact, this pressure distribution must satisfy the equation of continuity in a similar manner to the normalized velocity terms previously demonstrated. For this, (10.21a and 10.21b) is substituted into (10.18). After performing the differentiation and integration, this calculation returns:

$$\begin{aligned} [v]_0^{h(x,t)} = & -\frac{\partial}{\partial x} \left[\frac{1}{2\mu} \frac{\partial p}{\partial x} \int_0^{h(x,t)} (y^2 - yh) dy \right] - \frac{\partial}{\partial z} \left[\frac{1}{2\mu} \frac{\partial p}{\partial z} \int_0^{h(x,t)} (y^2 - yh) dy \right] \\ & - \frac{\partial}{\partial x} \int_0^{h(x,t)} \left[\left(1 - \frac{y}{h}\right) U_1 + \frac{y}{h} U_2 \right] dy + U_2 \frac{\partial h}{\partial x} \end{aligned} \quad (10.22)$$

Realizing that

$$[v]_0^{h(x,t)} = -(V_1 - V_2) = \frac{dh}{dt} \quad (10.23)$$

where V_1 and V_2 are the normal or approach velocities also known as entraining velocities in bearing applications, the generalized Reynolds equation that governs the pressure distribution in a lubricant film can be determined as shown in (10.24) [7, 20, 92]:

$$\begin{aligned} \frac{\partial}{\partial x} \left(\frac{h^3}{\mu} \frac{\partial p}{\partial x} \right) + \frac{\partial}{\partial z} \left(\frac{h^3}{\mu} \frac{\partial p}{\partial z} \right) = & 6(U_1 - U_2) \frac{\partial h}{\partial x} + 6h \frac{\partial(U_1 + U_2)}{\partial x} \\ & + 12(V_2 - V_1) \end{aligned} \quad (10.24)$$

Now, to simulate a conventional thrust bearing where the relative motion between the surfaces in contact is pure translation and then by assuming that $\frac{\partial(U_1+U_2)}{\partial x} = 0$, (10.24) would simplify to

$$\frac{\partial}{\partial x} \left(\frac{h^3}{\mu} \frac{\partial p}{\partial x} \right) + \frac{\partial}{\partial z} \left(\frac{h^3}{\mu} \frac{\partial p}{\partial z} \right) = 6(U_1 - U_2) \frac{\partial h}{\partial x} + 12(V_2 - V_1) \quad (10.25)$$

In another example, to simulate a traditional journal bearing where relative motion of the surfaces in contact is not parallel, a component of the rotational velocity would augment the relative motion in the tangential direction. This would cause (10.24) to simplify to

$$\frac{\partial}{\partial x} \left(\frac{h^3}{\mu} \frac{\partial p}{\partial x} \right) + \frac{\partial}{\partial z} \left(\frac{h^3}{\mu} \frac{\partial p}{\partial z} \right) = 6(U_1 + U_2) \frac{\partial h}{\partial x} + 12(V_2 - V_1) \quad (10.26)$$

In these two examples, thrust bearings and the journal bearings differ by the velocities contributing to the pressure generated. In thrust bearings, the difference in tangential velocities creates pressure, whereas in journal bearings the sum of the tangential velocities creates pressure [23]. With this notation, in a journal bearing, if the journal and the bearing rotate in opposing directions with similar velocities, there would be no pressure generated. Furthermore, in both thrust and journal bearings, positive pressures are generated only when the fluid film is convergent in both space and time as indicated by (10.27):

$$U_0 \frac{\partial h}{\partial x} < 0, \frac{\partial h}{\partial t} < 0 \quad (10.27)$$

The Reynolds equation derived in (10.17) provides a relationship between the film thickness and the fluid pressure in a fluid-film liquid lubrication system. This equation forms the foundation of fluid-film lubrication theory and establishes the relationship between geometry of the surfaces, relative sliding velocity, the property of the fluid, and the magnitude of the normal load a bearing can theoretically support [94]. The first two terms on the left side of (10.24) represent the Poiseuille flow, the first and second term on the right side represent Couette flow, and the last term on the right side signifies the squeeze flow. Currently, there is no closed form solution to the Reynolds equation. Many solutions utilize boundary conditions and simplification techniques to solve this numerically.

5 Conclusion

The advancements in lubricants have become an integral part of the development of machinery and various corresponding technologies. Lubricants and lubrication techniques are linked to numerous fields of expertise, and without this interdisciplinary aspect, the progression of lubricants and many applications may have failed to achieve success. Lubrication is a vital segment of tribology with implications affecting world energy usage, system reliability, application feasibility, the environment, and financial stability. With more than 10,000 different types of lubricants and an abundance of additives, selecting the appropriate lubricant for a particular application is not obvious. Lubrication engineers must have an understanding of the performance demands of the application and the composition of the lubricating materials before selecting a lubricant that has appropriate physicochemical properties that are not detrimental to the system.

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Exercises

1. Define the term “lubricant” and explain its importance in tribology.
2. Define the term “additive.” Why are additives used in lubricants? List various families of additives.
3. Explain the various lubrication regimes.
4. What is the Stribeck curve? Define Hersey’s number.
5. Explain how lubrication regimes can be determined based on oil-film thickness and roughness of the contacting surfaces.
6. Explain various temperature characteristics of lubricants.
7. Explain:
 - (a) Pour point vs. cloud point
 - (b) Flash point vs. fire point
 - (c) Volatility vs. evaporation
 - (d) Oxidation vs. thermal stability
8. Write a note on:
 - (a) Boundary additives
 - (b) Extreme pressure additives
 - (c) ZDDP
 - (d) Oxidation inhibitors
 - (e) Corrosion inhibitors
9. What is the underlying difference between thrust bearings and journal bearings in regard to the Reynolds equation? Provide the Reynolds equation for both bearing types.

Answers

1. A lubricant is a substance introduced between two moving surfaces to reduce friction, minimize wear, distribute heat, and remove foreign contaminants to ultimately improve efficiency. Lubricants are important because they allow mechanical components to achieve the desired amount of work while minimizing the amount of energy required to perform the work.
2. Additives are substances used to improve the performance of lubricants. Additives are selected based on their ability to reduce friction and wear, increase viscosity, improve viscosity index, resist corrosion and oxidation, increase component and lubricant lifetime, and minimize contamination. The main families of additives are antioxidants, antiwear formulations, antifoaming agents, corrosion inhibitors, detergents, dispersants, extreme pressure, friction modifiers, metal deactivators, and viscosity index improvers.

3. The three main regimes of lubrication can be referred to as boundary lubrication, mixed/elastohydrodynamic lubrication, and full film hydrodynamic lubrication. Boundary lubrication or boundary friction is the lubrication regime with the most asperity contact between the surfaces occurring due the presence of a thin fluid film. Mixed film lubrication is the combination of full film hydrodynamic lubrication and boundary lubrication. In this lubrication regime, the surfaces are transitioning away from boundary lubrication into hydrodynamic lubrication where there may be frequent asperity contacts, but at least a portion of the bearing surface remains supported partially by a hydrodynamic film. Hydrodynamic lubrication also known as fluid-film or thick-film lubrication involves two nonparallel surfaces in relative motion with a layer of fluid pulled in between the surfaces to develop adequate dynamic pressure to support the load of the opposing surfaces and prevent asperity contact. In this lubrication regime, the surfaces are no longer in contact and the fluid has established itself in significant form to create a thick film.
4. The Stribeck curve is a plot of the variation of the coefficient of friction against a nondimensional number, known as Hersey's number (also referred to as the Stribeck number), which is instrumental in demarcation of the lubrication regimes. Hersey's number is given as $(\eta v/p)$, where "η" is the lubricant viscosity, "v" is sliding velocity, and "p" is load per unit width.
5. Lubrication regimes can be determined based on oil-film thickness and roughness of the contacting surface by using the Hamrock and Dowson formula given as

$$\lambda = \frac{h}{\sigma} \quad (10.28a)$$

$$\sigma = \sqrt{\sigma_1^2 + \sigma_2^2} \quad (10.28b)$$

Here, (10.28a) is the ratio of the fluid-film thickness, h , and the composite surface roughness, σ . In (10.28a), the composite surface roughness is given in (10.28b) where σ_1 and σ_2 are RMS roughness of the two mating surfaces. Equation (10.28a and 10.28b) allows for the calculation of the minimum film thickness in lubricated contacts. The fluid-film thickness parameter, λ , decides the lubrication regime with boundary lubrication characterized by a value of λ less than 1, mixed or elastohydrodynamic lubrication described as $1 \leq \lambda \leq 3$, and hydrodynamic lubrication characterized by a value of λ greater than 3.

6. The important thermal properties of lubricants are specific heat, thermal conductivity, and thermal diffusivity. These three parameters are important in assessing the heating effects in lubrication, i.e., the cooling properties of the oil and the operating temperature of the surfaces. The temperature characteristics are important in the selection of a lubricant for a specific application.

7. (a) The pour point of a liquid is the lowest temperature at which it becomes semisolid and loses its flow characteristics. The cloud point of a fluid is the temperature at which dissolved solids are no longer completely soluble, precipitating as a second phase giving the fluid a cloudy appearance.
(b) The flash point of a lubricant is the temperature at which its vapor will flash ignite. The fire point of oil is the temperature at which enough vapor is produced to sustain burning after ignition. The fire point is higher than the flash point.
(c) In many applications the loss of lubricant due to evaporation can be significant. At elevated temperatures, in particular, oils may become more viscous and eventually dry out due to evaporation. Volatility of lubricants is expressed as a direct measure of evaporation losses.
(d) Oxidation stability is the resistance of a lubricant to molecular breakdown or rearrangement at elevated temperatures in an open-air environment containing oxygen. Thermal stability is the resistance of the lubricant to molecular breakdown or molecular rearrangement at elevated temperatures in the absence of oxygen.
8. (a) Adsorption or boundary additives control the adsorption type of lubrication and are also known as “friction modifiers,” since they are often used to prevent stick-slip phenomena. Adsorption or boundary additives are vital in boundary lubrication. Examples of additives in current use are fatty acids, esters, and amines derived from fatty acids.
(b) Extreme pressure (EP) compounds are designed to react with metal surfaces under extreme conditions of load and velocity to prevent welding of the moving parts that would otherwise cause severe damage.
(c) ZDDP is a very important antiwear additive commonly used in engine oil formulations. It was originally developed as an antioxidant and detergent, but was later revealed to exhibit superior antiwear properties and function as a mild EP additive.
(d) Many lubricating oils contain antioxidant additives to delay the onset of severe oxidation of the oil. These are either natural antioxidants or artificially introduced additives that are able to suppress oxidation.
(e) Corrosion control additives are classified as corrosion inhibitors and rust inhibitors. Corrosion inhibitors are used for nonferrous metals and are designed to protect their surfaces against any corrosive agents present in the oil. Rust inhibitors are used for ferrous metals to protect ferrous surfaces against corrosion.
9. Thrust bearings and the journal bearings differ by the velocities contributing to the pressure generated. In thrust bearings, the difference in tangential velocities creates pressure, whereas in journal bearings the sum of the tangential velocities creates pressure.

To simulate a conventional thrust bearing where the relative motion between the surfaces in contact is pure translation, the equation of motion is

$$\frac{\partial}{\partial x} \left(\frac{h^3}{\mu} \frac{\partial p}{\partial x} \right) + \frac{\partial}{\partial z} \left(\frac{h^3}{\mu} \frac{\partial p}{\partial z} \right) = 6(U_1 - U_2) \frac{\partial h}{\partial x} + 12(V_2 - V_1)$$

To simulate a traditional journal bearing where relative motion of the surfaces in contact is not parallel, a component of the rotational velocity augments the relative motion in the tangential direction resulting in an equation of motion as follows:

$$\frac{\partial}{\partial x} \left(\frac{h^3}{\mu} \frac{\partial p}{\partial x} \right) + \frac{\partial}{\partial z} \left(\frac{h^3}{\mu} \frac{\partial p}{\partial z} \right) = 6(U_1 + U_2) \frac{\partial h}{\partial x} + 12(V_2 - V_1)$$