

## CHAPTER 2

### LITERATURE REVIEW

#### Tribology

Tribology is the science of friction and lubrication and its technical applications and deal with the related problems of wear, material and design. Applied tribology is concerned primarily with the maintenance of machines, lubricant supply and standardization in the workshop, minimization of energy losses through friction and protection of the environment as related to lubrication. The essential tasks of tribology are to reduce friction and wear and thus to save energy and maintain the production facilities ; furthermore, to keep machines operational at low cost through adequate lubrication and maintenance.

#### Friction

Friction is defined as the force resisting the relative motion of two contacting bodies. We can distinguish between adhesive and kinetic friction whereby the adhesive friction is always the larger one. In the case when the sliding surfaces are in direct contact we have dry and solid friction , when they are separated by a solid, liquid or gaseous medium we speak of lubricated or fluid friction.

The region of transition from lubricated to dry friction is called mixed friction where both types of friction occur simultaneously. Boundary friction represents a case of mixed friction in the region of transition to dry friction. Friction losses occur in the case of sliding as well as rolling friction, however, the energy losses are much smaller in the later case. A parallel relationship exists between friction and wear (Table 2.1).

Table 2.1 Relationship between Friction and Wear.

Friction regime	Friction Coefficient (approx. value)	Wear
Dry friction (sliding)	0.30	high
Dry friction (rolling)	0.005	very low
Mixed friction (rolling)	0.005 - 0.3	noticeable
Fluid friction	0.005 - 0.1	practically zero

Friction is a function of the size of the contacting surface area. The postulation that friction is independent of the sliding speed cannot be

maintained, since the friction coefficient is not a material constant, but depends on the surface roughness of the sliding elements, the sliding speed, and the selection of materials for the sliding pairs, separated by a suitable medium (lubricant), is subject to other factors and laws.

## Viscosity

In the past viscosity was usually known as the "coefficient of internal friction". However, in 1866 Clerk Maxwell had given the definition of "viscosity" or the "coefficient of viscosity". His definition is valid for and fluid in laminar motion. It is reproduced here in full :

This coefficient may be best defined by considering a stratum of air between two parallel horizontal planes of indefinite extent at a distance  $a$  from one another. Suppose the upper plane to be set in motion in a horizontal direction with a velocity of  $v$  feet per second, and to continue in motion till the air in the different parts of the stratum has taken up its final velocity, then the velocity of the air will increase uniformly as we pass from the lower plane to the upper. If the air in contact with the planes has the same velocity as the planes themselves, then the velocity will increase feet per second for every foot we ascend.

The friction between any two contiguous strata of air will then be equal to that between either surface and the air in contact with it. Suppose that this friction is equal to a tangential force  $f$  on every square foot, then

$$f = \mu \frac{U}{a} \quad (2-1)$$

where  $\mu$  is the coefficient of viscosity  
 $U$  is the velocity of the upper plane  
 $a$  is the distance between them

## Lubrication

### 1. Lubrication Regimes

The main function of lubricating oil is to reduce the friction between sliding surfaces, to prevent wear, to remove heat of friction and wear from the load carrying zone and to prevent the penetration of foreign matter into the lubrication clearance. One distinguishes between total and partial lubrication. In the case of total lubrication the sliding partners are completely separated by a lubricant film and do not get into contact with

each other even at increased loads, for example hydrodynamic and hydrostatic lubrication . In the case of partial lubrication all intermediate stages of dry and mixed friction , as well as boundary lubrication may occur Elastohydrodynamic lubrication (EHD) occurs in the region of very high loads and in the case of badly adjusted sliding partners.

The influence of the lubricant viscosity  $\eta$  , the bearing load  $p$  and the sliding velocity ( $\omega$  = angular velocity) on the working vegin and friction of a plain bearing is shown by the STRIBECK curve, on cveniently expressed not through the rotation speed but through the dimensionless "bearing paramenter"; the curve represents all significant parameters and avoids the need for a multitude of individual curves (Fig 2.1).

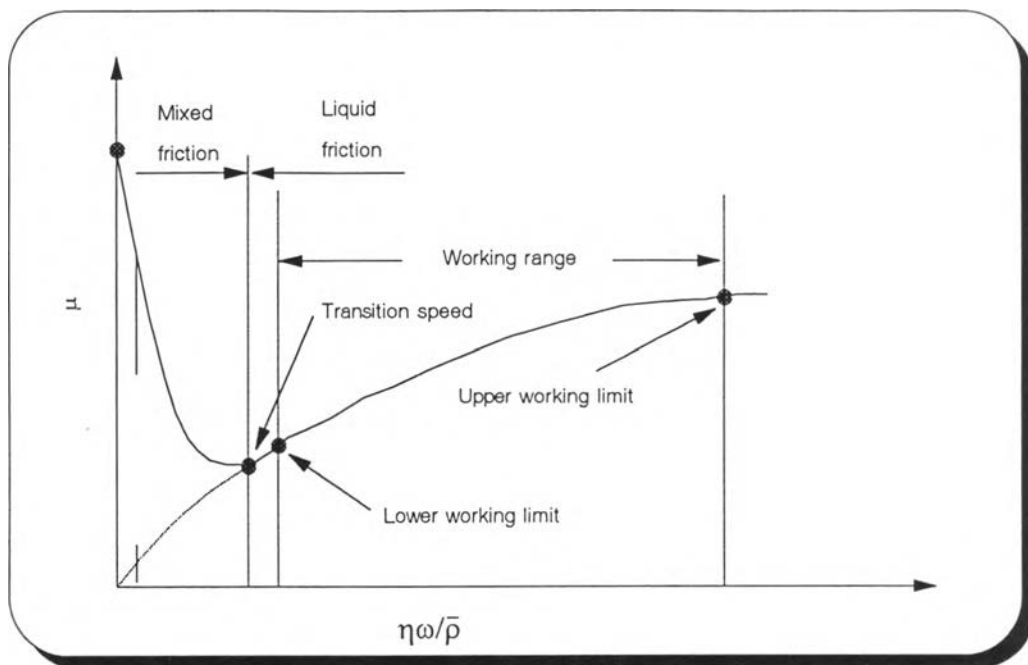


Figure 2.1 Friction coefficient  $\mu$  as function of the expression  $\eta\omega/p$  for a plain bearing (STRIBECK curve)

According to

$$\mu = k \cdot \eta\omega/p \quad (2-2)$$

Equation 2-2, a decrease in viscosity caused by an increase in temperature or shearing shifts the working range of a bearing towards fixed friction.

## 2. Hydrodynamic Lubrication

Hydrodynamic lubrication is achieved by movement of a liquid. The increase in pressure in the lubrication clearance of rotating bearing was first observed by Tower in 1883. His measurement showed that the lubricant pressure was significantly higher than the load on the bearing and that pressure distribution was created in the bearing. In 1886 O. Reynolds attributed this phenomenon to the formation of a hydrodynamic liquid film by the rotating shaft, which pulls the liquid lubricant into the conical converging clearance between bearing shell and shaft and thus creates the dynamic pressure which carries the shaft (Fig 2.2).

The differential equation below describes the movement of the surface of a three-dimensional liquid layer in the direction of rotation (x axis);  $h$  is the layer thickness (y axis);  $v$  is the constant speed,  $p$  is the pressure and  $\eta$  is the dynamic viscosity; the  $z$  axis indicates the width.

$$\frac{\partial}{\partial z} \left( \frac{h^3}{6\eta} \frac{\partial p}{\partial z} \right) - \frac{\partial}{\partial x} \left( \frac{h^3}{6\eta} \cdot \frac{\partial p}{\partial x} \right) = \frac{\partial}{\partial x} (v \cdot h) \quad (2-3)$$

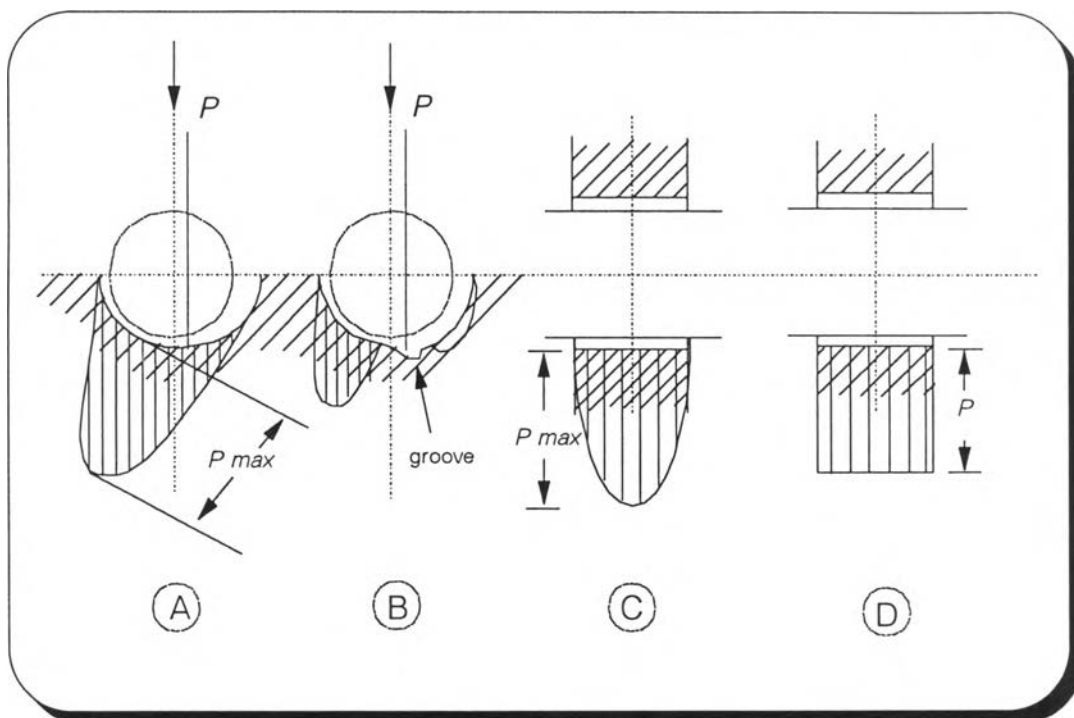


Figure 2.2 Pressure changes in a stationary journal bearing with and without oil groove A:Pressure change in smooth bearing shell, B:Pressure changes in shell with groove, C:Pressure drop at bearing sides, D:Pressure profile in the absence of lateral leaks.

It assumes Newtonian flow characteristics and laminar flow, incompressibility and a constant viscosity of the medium and negligibly small inertia force of the liquid particles. According to Eq. (2-2), the effective viscosity of the liquid and its velocity in the lubrication clearance are responsible for the formation of a load-carrying lubricant film. The high shear rates created in plain bearings at high speeds can lead to a change from laminar flow in the lubricating clearance to turbulent flow, to which the hydrodynamic equation do not apply. A significant increase in the sliding resistance and the resulting increase in bearing temperature reduce the clearance of the bearing and the viscosity. The flow is characterized by the dimensionless Reynolds Number  $Re$ ;

$$Re = \frac{U \cdot d}{\nu} \quad (2-4)$$

where  $U$  is velocity of liquid film,  $d$  is the mean clearance between shaft and bearing, and  $\nu$  is the kinematic viscosity at the working temperature. The flow in plain bearing is laminar below  $Re = 1900$  and turbulent above this value.

### 3. Hydrostatic Lubrication

In hydrostatic lubrication, an auxiliary pump located outside the bearing is used to create the lubricant pressure required to separate the sliding elements. Thus, the pressure can be adjusted regardless of the relative speed of the sliding partners, even when they are stationary. Hydrostatic or pressure chamber bearings are being used when wear must be avoided in all operating regimes and/or low or constant friction coefficients are required: at low speeds and high loads (rolling mill train bearings, water turbines, generators), for work spindles of ultra-high precision machine tools (grinding machines), and for slow-speed slideways or joints operating under high loads. However, the advantages achieved in permanent operation must be compared with the extra costs for the installation and operation of the pumps and the oil pressure control devices.

In the case of radial bearings the lubricant is supplied at the point at which the shaft would rest on the bearing. In order to prevent instabilities and large shifts of the shaft at high speeds or when changing the direction of rotation, i.e. between the loaded and unloaded state, these bearings are designed as triple or multiple surface bearings with separate lubricant supply.

The single or multiple surface bearing carries at each level centrally arranged lubricating pockets through which the oil is pumped so

that it leaves the bearing radially and forms a coherent lubricant film. A lubricant flow is required to obtain an oil film with the thickness, which is a function of the oil viscosity and the pressure drop between oil inlet and oil outlet at the edge of the bearing.

#### 4. Boundary Lubrication

In most normal situations rough surfaces are initially coated with a film of oxide, iron oxide on iron or steel, aluminium oxide (alumina) on aluminium, and so on. When such surfaces rub together, their tendency to adhere is relatively mild. However, if the oxide film is removed by vigorous rubbing, the exposed metal surfaces have a very powerful tendency to adhere.

Thus if the bearing surfaces retain their oxide films the contact between asperities will give moderate friction and mild wear. If they lose their oxide films there will be high friction and severe wear. In either case the object of boundary lubrication is to reduce friction and wear, and there are several ways in which this can be done.

##### (a) Adsorption

All solid surfaces tend to attract a thin film of some substance from their environment. Such films may be only one or a few molecules thick, and are said to be "adsorbed" onto the surface. The process is shown diagrammatically in Figure 1.6, in which molecules of a long-chain alcohol are depicted adsorbed onto a metal surface.

The strength of adsorption depends on the electronic structure, and "polar" molecules (those in which there is a variation in electronic charge along the length of the molecule) tend to adsorb with their molecules perpendicular to the surface. Thicker or more strongly adsorbed films will give greater protection to the bearing surface, so the preferred boundary lubricants for adsorption onto a bearing surface are long-chain polar organic chemicals, and these will be considered in a later chapter.

Adsorption is a reversible process, and an adsorbed substance can be desorbed, if heated to a critical temperature, or displaced by a substance which is more strongly adsorbed. This latter effect is valuable in boundary lubrication because the most strongly adsorbed substances present in the lubricant will be preferentially adsorbed, and in a well-formulated lubricant these will be the more effective boundary lubricants.

A useful by-product of adsorption is the so-called "Rehbinder Effect", the reduction of the modulus and yieldstress of metals in the

presence of an adsorbed film. As a result of this effect, lower stress is developed when asperities collide. In particular, during the running-in of new bearing surfaces, the removal of excessive asperities will take place more mildly.

#### (b) Chemisorption

After adsorption onto a metal surface, some substances will react with the metal or oxide surface to produce a new chemical compound. Such substances are said to be "chemisorbed", an example is the chemisorption of stearic acid on an iron-containing surface as iron stearate. Chemisorbed materials are more strongly bound to the metal surfaces than are adsorbed materials, and the chemisorption process is not reversible. Long-chain molecules again orient themselves perpendicular to a surface, and such films can give very effective boundary lubrication.

#### (c) Chemical reaction

Adsorbed and chemisorbed films are very effective in reducing friction and mild wear under light or moderate rubbing. They are fairly easily removed mechanically under severe rubbing conditions and are therefore not very effective in preventing severe wear or seizure. The natural oxide layer reduces severe wear and seizure, but once it has been removed by rubbing, the re-oxidation of the surface may be too slow to be effective.

To handle such situations, more reactive chemicals can be added to the lubricant to react with the bearing surfaces and produce protective films. Suitable films include chlorides, iodides, sulphides, phosphides and phosphates, and any chemical which will react with a bearing surface to produce such substances will be effective in producing protective films. The problem is that really reactive chemicals such as hydrochloric or phosphoric acid will continue to react, and will thus corrode away the metal surface.

The solution is to use organic compounds containing sulphur, phosphorus or chlorine, which may adsorb or chemisorb on oxidised metal surfaces but will react rapidly with freshly exposed metal surfaces from which the oxide film has been removed. For example, tri-xylol phosphate will chemisorb onto oxidised bearing steel, but under severe rubbing will react with freshly exposed steel to produce surface layers of iron phosphate or phosphide.

In this way the reaction of the chemical with the bearing surface can be limited to the minimum necessary for lubrication, and corrosion is controlled. Even so, some of the more powerful extreme-pressure

additives will slowly attack some metals, and should only be used where rubbing conditions are very severe, such as in metal cutting.

An indication of the effectiveness of such films is given by the use of processes such as phosphating and sulphiding on new rubbing surfaces to prevent seizure during running in.

### 5. Externally pressurised Lubrication

In section 2.4.2 it was explained how the pressure necessary to give full fluid film separation of loaded bearing surfaces is produced by the movement of the surfaces. The same effect can be obtained by forcing the lubricant into the bearing under an externally applied pressure, and this will enable full fluid film separation to be achieved where the viscosity or speed would be insufficient to support the load hydrodynamically.

The basic theory of externally pressurised (sometimes called hydrostatic) lubrication is very simple. The average pressure required is equal to the load divided by the effective bearing area.

$$P = \frac{W}{A} \quad (2-5)$$

In practice the design of hydrostatic bearings must also take into account the need to maintain stability and to control lubricant flow. External pressurisation may be used with a liquid lubricant or even a grease but it also commonly used with a gas, where it can offset the problems associated with the very low viscosity of gases.

### **Lubricating oils**

In the early history of lubricants, animal and vegetable oils were used as lubricants in transportation and machinery. There was a development in use of lubricant during AD 450-1450. However, the value of lubricants in decreasing friction and wear was found during industrial revolution in AD 1750-1850. The studies of friction showed that surface roughness was the major factor effecting the resistance to sliding between two surfaces. Therefore, it was thought that lubricants were effective because they filled up the hollow in surfaces and reduce the roughness. However, the studies of Tower (1883) and Petrov (1883) clearly indicated that in successful bearings the rotating journal was completely separated from the bearing by a lubricant film. Three years later (1886) Reynolds recognised the principle of fluid-film lubrication when he carried out the study of the slow,



viscous flow of lubricants in plain bearings and derived the differential equation which is described in section 2.4.2 .

### 1. Petroleum Base Oils

As mention in the previos section base fluids are the major components in lubricating oils which provide liquid film lubrication to the oil. There are many types of base fluids used to make lubricants. They can be classified into catigories.

1. Petroleum base oils
2. Vetgetable and animal oils
3. Systhetic base fluid

According to their low prices and good general properties, petroleum base oils are widely used in most of lubricating oil. Vetgetable and animal oils have been used as lubricants for long time since the early history of lubricants. Vetget- able and animal oil provide very good lubricity property but poor aging tendency. Due to this problem the use of vegetable and animal oil has decreased. However, because of verygood lubricity property, these kinds of oil are still used as additives in lubricants especially in metalworking oils.

For system that operated at severe condition, such high temperater and high load, the special formulated oil is require to provide good oxidation resistance, good lubricity, long service life. In this case, synthetic base fluids are used. The examples of systhetic oils are polyalphaolefin, polyether oils such as polyalkylene glycols and polyphenyl ethers, phosporic acid esters, esters of carboxylic acids, hologenated hydrocarbons and halocarbons, etc. However, these specialoils are very expensive.

Petroleum base oils are the products from the refining process of crude oil. It is believed that crude oil originated from the remains of plants and animals burried underground. As successive layers built up, those diposits were subjected to high temperatures and pressures and as a result underwent chemical tranformations leading to the formation of the hydrocabons and other constituents of crude oil. Crude oil are found in a rariety of types ranging from light colored oils, consistingmainly of gasoline, to black, nearly solid as phalts Figure 2.3 shows typical hydrocarbon configurations present in crude oils. The hydrogen carbon atom structures vary a great deal as do the impurities, such assulfur or wax, in the crude oil. Some crudes are suitable only for the manufacturing of gasoline, diesel, fuel oil and by-products. While othersare prepare for the manufacturing of fine lube oil stocks.

There are three basic types of crudes

1. Paraffinic
2. Intermediate, naphthenic, or mixed base
3. Asphaltic

The different basic crude stocks may be more suitable for one type of application than for another. It would not be cost-effective to use a fine paraffinic stock oil for open gear lubricants where a poor quality asphaltic stock oil would perform fine Likewise, to use an asphaltic stock oil for high-performance hydraulic oils would not make sense.

The components of crude oil can be classified into two major categories as follow.

1. *Hydrocarbons* Hydrocarbons are the arganic compound composed of carbon and hydrogen which present as the major components in all crude oil. They can be further subdivided :

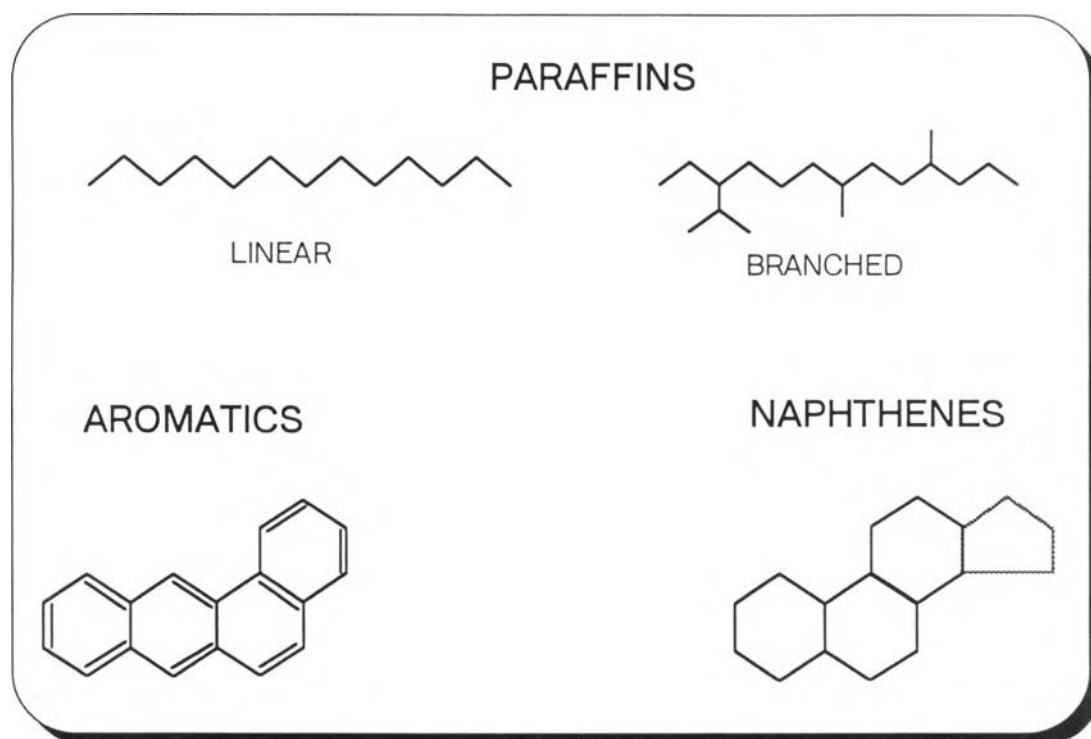


Figure 2.3 Examples of hydrocarbons

This classification is a simplification because there are many hydrocarbons which are combinations of these classes, for example

alkyl-substituted cyclics or mixed polycyclics containing both aromatic and fully saturated rings.

**2. Non-hydrocarbons** Many organic compounds in crude oil incorporate other elements sometimes within ring structures or as functional groups attached to a hydrocarbon structure. Organosulphur compounds are generally much more prevalent than nitrogen or oxygen-containing molecules, while organometallics are usually present as traces.

Within the boiling range appropriate to lubricant base oils, almost all of the organosulphur and organonitrogen compounds are heterocyclic molecules. In contrast, the principal oxygen-containing molecules are carboxylic acids; either saturated aliphatic acids or cycloalkanoic acids (naphthenic acids). Traces of phenols and furans may also occur.

Finally, there are very high molecular weight resins and asphaltenes which contain a variety of aromatic and heterocyclic structures. Resins are the lower.

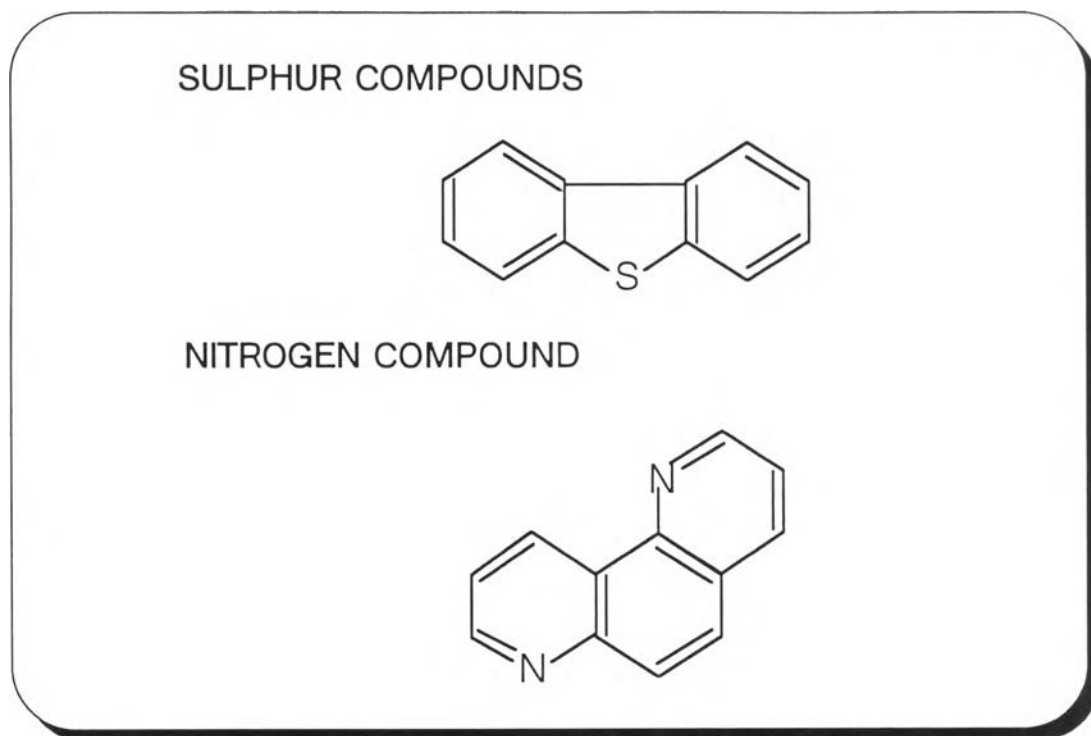


Figure 2.4 Non-hydrocarbon examples

Paraffinic and intermediate (mixed) stocks tend to make up the majority of the lube oil stocks today. Even then, the stocks are selected and segregated according to the principal types of hydrocarbons present in

them. The types of lube oil stocks present, after distillation, are carefully monitored, tested, and selected for certain applications, such as motor oil, hydraulic oil, turbine oil, and grease applications.

A lube oil stock from paraffinic crude would contain wax and have a higher pour point because of the wax crystals, even though much of the wax is removed as part of the refining process. Paraffinic stock oils also have a higher viscosity index, which makes them more suitable for applications such as hydraulic and automotive products which are used over a wide temperature range and require good natural viscosity index and oxidation resistance.

A lube oil stock from naphthenic crude (mixed) contains essentially no wax and therefore will have a much lower natural pour point. It will also have a very low viscosity index, making it less suitable for a lubricant which must operate over a wide range of temperature. Naphthenic stock oils are typically used in products such as some gas engine oils, refrigeration oils, and railroad engine oils.

The different types of crude oil allow refiners to select those which, when fully refined, will provide base stocks suitable for their needs. Quality and types of stock oils vary, and they are traded and purchased between major companies according to their needs. The refining process is much too complex to detail at this time. Many processes are used to remove most of the undesirable elements from the stock oils to make them more suitable as a lubricant. These refining processes can produce by-products, such as wax, which can be profitably sold to industry. Millions of pounds of wax are consumed yearly by the companies who make paper matches. A stock oil may also be subject to solvent extraction and/or hydrofinishing to produce a finished base stock oil.

## 2. Additives

Base oils alone can no longer satisfy the requirements of new technology machines and engines, since only few properties of base oils are improved by modern base oil production process. For this reason, additives are used to enhance the performance of petroleum base oils. By-products from petroleum processes or cheap basic material (sulphur) were firstly used as additives in 1910. In 1920, the development of special additives was started as well as the scientific and technical investigation of their effectiveness.

Some of the additives affect the physical properties of base oils, others have a chemical effect. Many modern additives have several functions. They are known as additive packages which are manufactured by

mixing of different kind of additives together. The followings are common additives used for manufacturing of high quality lubricants.

1. *Oxidation Inhibitors* i.e. Dialkyl phenol Sulfides, Zinc dialkyldithio - phosphate, 2,6-Di-tert-butyl-4-methylphenol, N-Salicylidene-ethylamine and etc.
2. *Viscosity Index Improver* i.e. Polyisobutenes, Polymethacrylic Acid Esters, Diene polymers, Polyolefins, Polyalkylstyrenes and etc.
3. *Pour Point Depressants* i.e. copolymer of vinylacetate and ethylene or of 1,2-epoxyalkanes such as 1,2-epoxytetradecane, Phthalic acid dialkylaryl esters, Long-chain alkyl phenol and etc.
4. *Detergents and Dispersants* i.e. Ca,Pb,Zn and Mn naphthenates with complex structures, Ca dichlorostearates, Metal petroleum sulfonates, Phenates, Sulfurized Phenates, Polyisobatenyl succinic Acid Derivatives and etc.
5. *Extreme-Pressure Additives* i.e. polysulfides, Butylphenol-disulfides, Sulfurized fattyoil, Chlorinated paraffins, phosphorus compounds such as Triphenyl phosphate, trioylel phosphate and etc.
6. *Friction Modifiers* i.e. Phosphoric or phosphonic acid and their derivatives, Amines, amides, imides and their derivatives, Caboxylic acids and etc.
7. *Antifoam Agents* i.e. liquid silicones, Polyethylene glycol ethers and sulfides, etc.
8. *Corrosion Inhibitors* i.e. alkaline-earth phthalylakylamides, amino- dicarboxylic acids, Fatty acid amides, Phosphoric Acid Derivatives, Sulphonic Acids, Carboxylic acid Derivatives,
9. *Other Additives* i.e. Emulsifiers, Demulsifiers, Dyestuffs, Odorants, etc.

### 3. Lube Oil Manufacturing

Generally, Lube oils are blend at 50–60 C. At this temperature the viscosities of base oils and additives are sufficiently low to guarantee satisfactory and rapid mixing. However, products containing solvents or low flash point base oils are blended at ambient temperature to avoid fire or explosion problem. At high temperature e.g. 100 C base oils and additives intend to decompose. Blending process may be batch process or continuous process.

For batch blending, the blending tanks or agitators are usually heated and equipped with stirrers. The quantities of components used are calculated from the percentages by weight in formulation. However, quantities by weight of components can be converted to volume if their densities are known. Mixing is best achieved with propeller stirrers (Fig. 2.5A). When a circulation pump is used, its capacity must be large enough to allow

several circulations of the oil volume per hour (Fig. 2.5B). The old method of stirring with air admitted to the blending tank at its lowest point is economical in cases where oxidation of the oil components at the blending temperature is not expected (Fig. 2.5C). However difficulties may be encountered by condensation water or oil mist entrained by compressed air drawn from a central system.

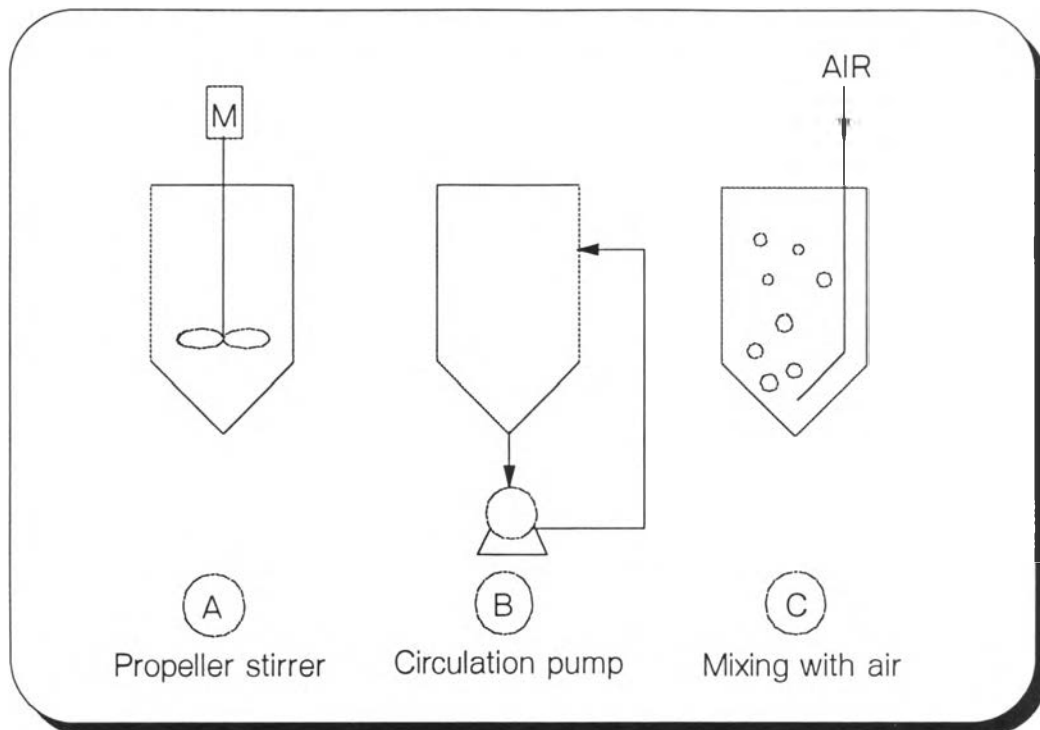


Figure 2.5 Types of blending agitators

In case of In-Line blending, all components, base oils and additives, are metered into a main stream. This is the economical method for blending large oil quantities. In the Cornell system (Fig. 2.6) two or more Synchronously driven dosage pumps are used, the volumetric throughput of which can be adjusted independently with great precision. A trouble-free operation requires free access of the components to the dosage pump. The Proportioners (Fig. 2.7) use a separate meter for each component; their rotations are transmitted mechanically to bevel gears which in turn are connected to planetary gears. When the planetary gears of the limiting (reference) component and the controlled component rotate at the same speed the required dosage rate has been reached. Any deviation from the preset ratio causes nonuniform movement of the level gears which alters the position of the planetary gear and thus the flowrate of the components. An advantage of the system is, that the whole equipment stops automatically when a deviation from the formulation occurs.

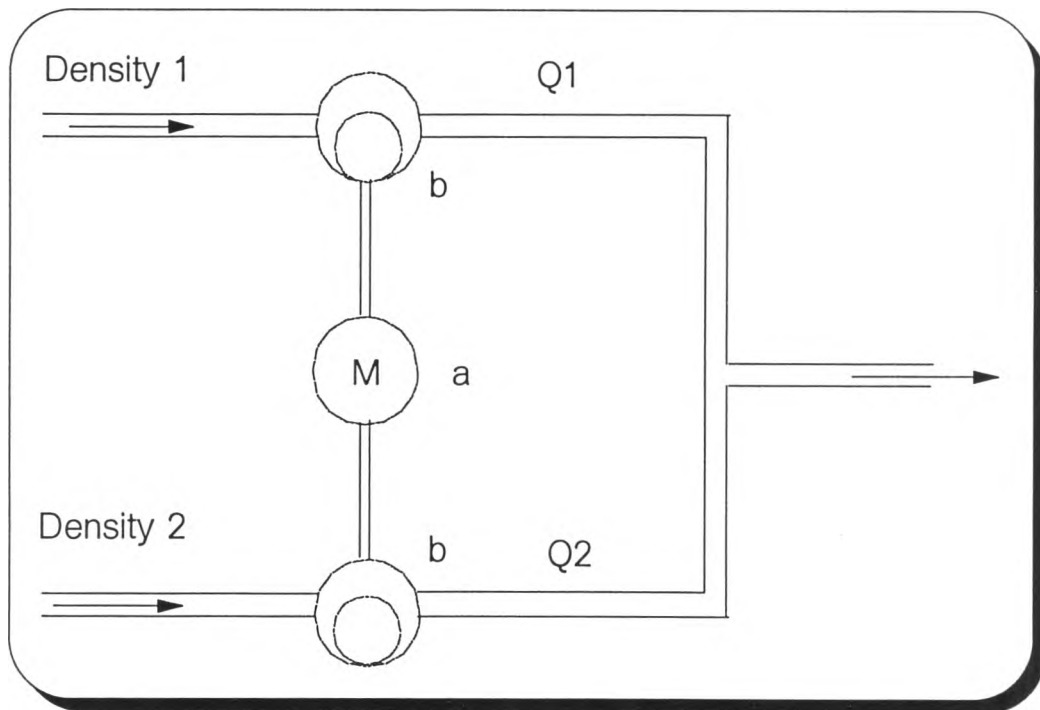


Figure 2.6 Continuous oil blending plants, system CORNELL ;  
a: Motor , b: dosage pump

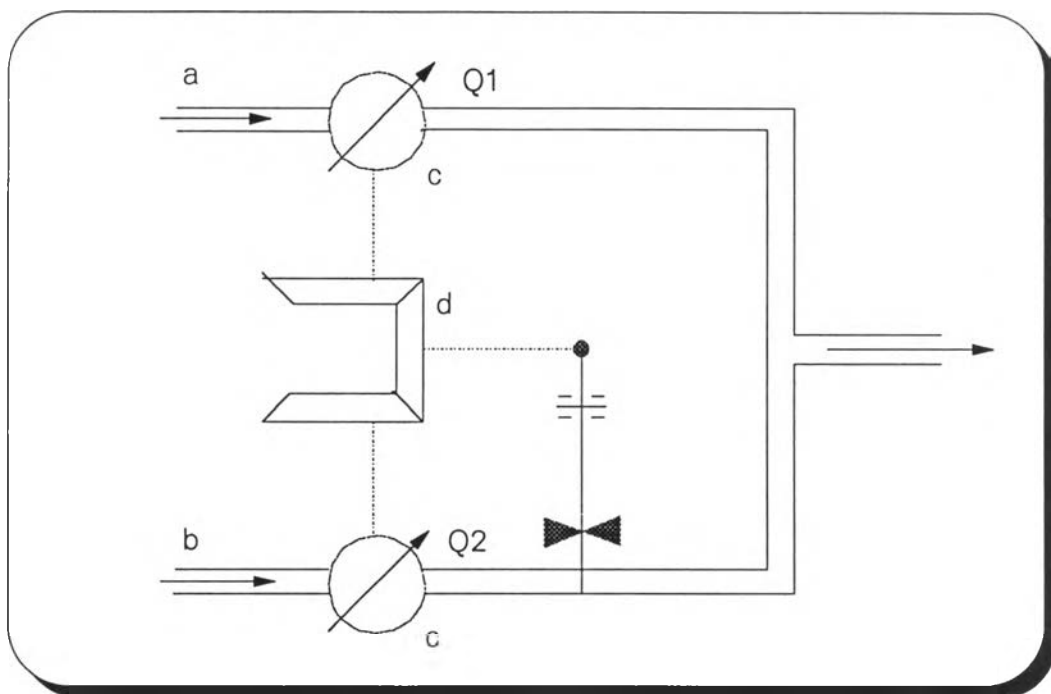


Figure 2.7 Continuous oil blending plant, system PROPORTIONNEES.  
a. Limiting (reference) component; b. following component;  
c. reciprocal (piston) counter; d. differential gear;  
e. control valve

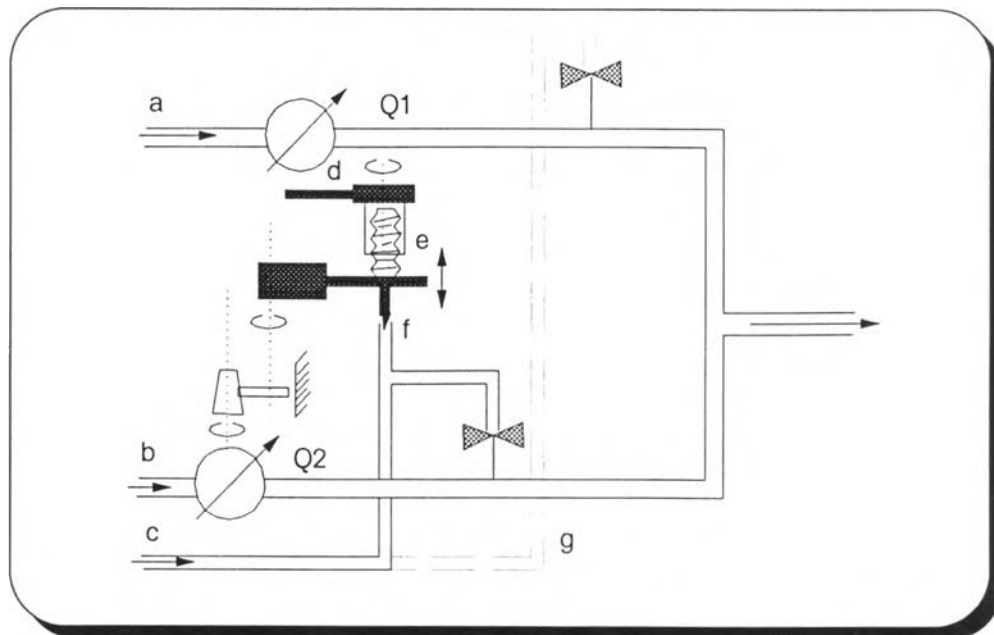


Figure 2.8 Continuous oil blending plant, System SIEMENS & HALSKE  
 a. Limiting component ; b. following component ; c. control air ; d. piston counter; e. differential screw drive ; f. control air nozzle ; g. control valve;

The blending plant of SIEMENS& HALSKE is based on a similar principle. The planetary gear is replaced by a threaded nut which alters the pulse of the control air, which in turn regulates the supply of the components (Fig. 2.8).

Today, the quantities of the individual components are measured and adjusted electronically. Many blending plants for lubrication oils in operations are based on the principle of a fully automatic blending plant (Blendomat), introduced in 1962 for the blending of motor gasolines, using to two base components and three additives. The number of components can be varied (Fig. 2.9).



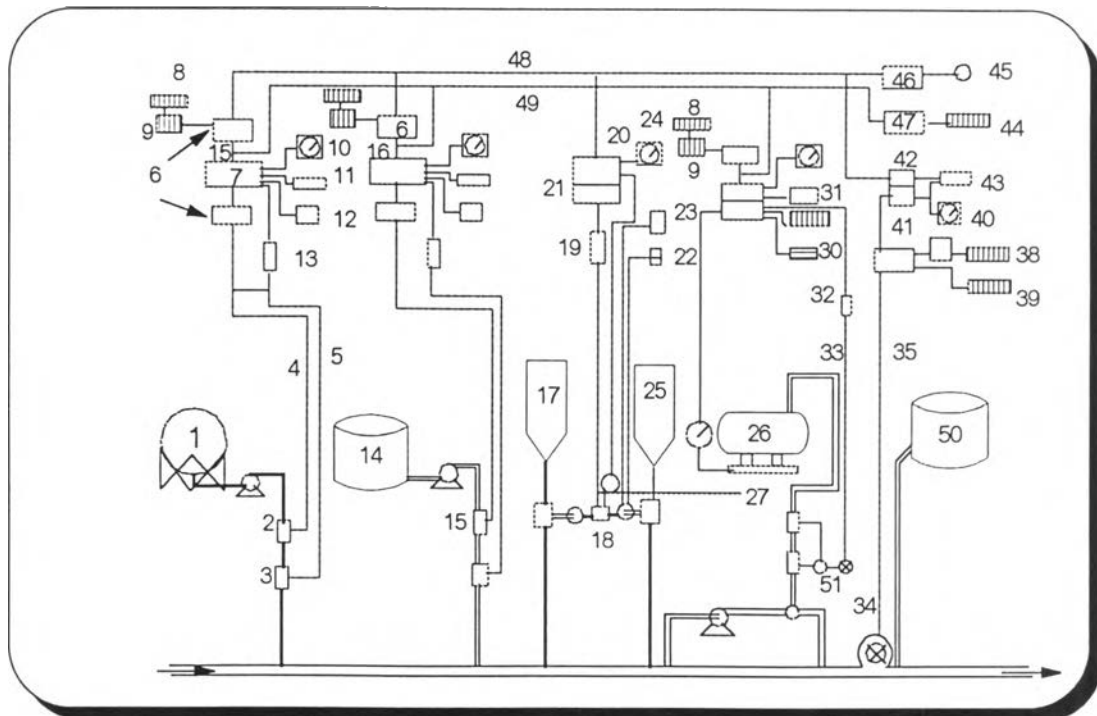


Figure. 2. 9 Automatic blending plant for two component and three additives. Component 1; 2 turbine flowmeter; 3 control valve with electropneumatic adjustment; 4 control Frequency, 5 adjusting current 4.2 mA; 6 multiplier; 7 digital volume control; 8 projection display; 9 % adjustment switch; 10 flow meter; 11 volume deviation; 12 discharge quantity, preselected; 13 valve adjustment; 14 component 2; 15 volume counter with temperature compensation; 16 nominal frequency; 17 additive; 18 discharge pump with adjustable stroke and speed; 19 excitation; 20 digital speed (revolutions) control; 21 amplifier ; 22 adjustment; 23 stroke-length (vol %); 24 number of revolutions; 25 dyestuff; 26 antiknock agent; 27 container weight bridge with pulse generator; 28 digital weight control; 29 counter; 30 net display; 31 quantity deviation; 32 nominal flow; 33 nominal throughput 4.20 mA; 34 main Counter; 35 pulses from main counter; 36 volume counter; 37 alarm adjustment; 38 nominal batch (m<sup>3</sup>); 39 actual remaining batch (m<sup>3</sup>), 40 total flow, scale display, 41 frequency meter; 42 frequency meter; 43 comparative display (guide frequency, total throughput; 44 projection display for adjustment control; 45 manual justment total flow; 46 guide frequency generator; 47 nominal value control; 48 guide frequency; 49 sum of nominal frequencies, 50 finished product; 51 FIC (volume control).

## Turbine Oils

As mentioned in Chapter 1, Turbine oils are classified into three categories based on the types of turbine engine which oils are used as lubricants. The following Sections explain the details of each type of turbine oil.

### 1. Gas Turbine Oils

The lubrication requirements of turbo-jet and turbo-fan engines are undemanding. The bearings are all rolling contact bearings in steady rotation at high speeds so it is easy to maintain full elastohydrodynamic film lubrication. There is a wide variety of other lubricated components such as couplings, gears, actuators and bearings associated with ancillary components, but these are small, with relatively low loads and powers, and can be kept clear of the high temperature zones of the engine.

For turbo-props, helicopter engines and propfans the most demanding lubrication requirements are those of the reduction gears. These carry high power, sometimes at high torque, and may be subject to fluctuation loading.

The critical requirement for all gas turbine lubricants is their ability to cope with a wide range of temperatures. The hottest lubricated components are the turbine bearings and some interesting design features are used to cool the turbine hub. In spite of this, the oil in the turbine bearings may be subjected to temperatures as high as 280 C. The residence time of the oil during normal operation is short, but after engine shut-down the bearing temperature will often rise even higher because of heat soak from the blades after the cooling air-flows have ceased. A small quantity of retained oil will therefore be exposed to very high temperatures until the bearings cool. At the other end of the temperature range, the oil must flow easily enough to permit engine starting at specified temperatures down to -40 or -54 C. If an engine must be restarted in flight, the ambient temperature may be even lower.

The earliest aircraft gas turbines were lubricated with highly refined mineral oils, and some mineral oils were still in use as late as 1958. The thermal stability and low temperature viscosity of even the best mineral oils were never completely adequate for the earliest days of gas turbine propulsion.

The potential of synthetic aliphatic esters as lubricating oils was recognised as early as 1936, and they were particularly investigated for use as instrument oils. They were probably first studied for use in gas

turbines in Germany, but by 1950 they had been accepted worldwide in the gas turbine industry. Their advantages included not only high thermal stability and good viscosity-temperature characteristics, but also low volatility, low foaming tendency, lack of corrosiveness and good boundary lubrication.

The existence of two fundamentally different classes of gas turbine lubricant is unsatisfactory for standardisation purposes and is a potential hazard, since the two classes are not considered as acceptable alternatives even for emergency use. An attempt was made therefore in the mid-1960s to introduce an intermediate type of oil with a 99 C minimum viscosity of 5.5 cSt which could replace the 3.0 cSt and 7.5 cSt oils, at least for future engines. This coincided with a new US Navy requirement for a similar oil for new turboprop aircraft. The new class of oil was introduced but has not helped to achieve standardisation on one grade. In fact engine manufacturers appeared to have seized with delight on the availability of three alternative viscosity grades for their later engines and all these grades are now in widespread use.

Apart from the use of viscosity index improvers, additives used in gas turbine lubricants include antioxidants, anti-wear additives, metal deactivators, corrosion inhibitors and anti-foaming agents. Like aviation piston engine oils, the oils used in aircraft gas turbines are tightly controlled by specifications. There are basically four classes of specification, all primarily military. Although the major engine manufacturers may have their own specifications, these are generally in line with the military specifications.

The four classes of specification are:

- (1) 3 cSt oils, originating in the US Air Force MIL-L-7808 specification and consisting of diesters/hindered esters with a small amount of additives but no viscosity index improver.
- (2) 7.5 cSt oils, originating in the British D.Eng.R.D. 2487 specification, and consisting primarily of diesters with viscosity index improver and small amounts of other additives.
- (3) 5 cSt oils meeting British specification D.Eng.R.D. 2497.
- (4) 5 cSt oils meeting the US Navy MIL-L-23699 specification.

## 2. Steam Turbine Oils

Steam turbines are lubricated by means of forced circulation systems; a pump, driven by the turbine shaft, transports the oil from the storage tank through a filter and oil cooler to the lubrication points. Highest demands are placed on the circulated oil by steam pressures of up to 175

bar and live steam temperatures of 600 C. The service life of the oils depends primarily on the design of the lubrication system and the quality of the oil. Although the bearings are insulated against radiant heat, the shaft before the journal bearing on the high-pressure side can reach 200 C at a steam inlet temperature of 600 C, so that considerable heat quantities have to be carried away. In spite of a low inlet temperature of 35–40 C and a average outlet temperatures of 60 C, the oil is strongly heated up locally. The simultaneous presence of steam, condensation water, air oxygen, metals and chemically active substances as well as the occurrence of leakage currents increase the requirements with respect to the aging stability of the oils. The most important property of a steam turbine oil is thus its aging stability since, besides performing its lubricating function, the oil must also carry away the heat created in the turbine bearings. Being in contact with steam and water, the turbine oils must also possess satisfactory water-shedding properties and provide protection against corrosion. A good resistance to air entrainment is required in order to prevent malfunction of the hydraulic system which controls the turbine speed. Aging products which are inclined to form precipitates can also seriously disturb the control system.

In order to provide a sufficient settling time for the separation of dirt, water and air, the amount of oil circulated must be calculated so that it is circulated about 8 times per hour. Very-fine dirt and aging particles are removed from the oil by filtration and occasional centrifuging in a side stream. Oil coolers prevent the oil temperature from rising too high and thus the viscosity from dropping below tolerable levels and premature aging of the oil. When transmissions are lubricated with turbine oils from the same circulation system, they should be designed for oils without antiwear additives. However, service lives of more than 25 years (as demonstrated in several power plants) can be achieved in critical gears when they are lubricated with turbine oils containing selected antiwear additives which must be resistant to hydrolysis and have no negative effects on the other oil properties. Such oils with antiwear properties have not yet been standardized; the minimum requirements for normal steam turbine oil (standard designation: L-TD lubricants) are given in DIN 51 515, Part 1. Oils which satisfy this standard are also suited for stationary gas turbines. In order to improve the safety of operation of turbine circulating systems fire-resistant phosphoric acid esters (see Sections 6.4 and 11.96) have been tried out, particularly for nuclear power stations, for the control circuits and also for lubrication of the turbine. In spite of their relatively good hydrolytic stability, these fluids require more attention in order to guarantee trouble-free operation than conventional turbine oils.

As in soluble cutting and rolling oils, in fuel storage systems and marine diesel engines microbial growth, with costly consequences in machine down-time, worker comfort and health hazards, clean-up time and

materials, fluid disposal and replacement can also occur in the lubricating oil systems of steam turbines.

All the requirements for bacterial growth are present: water, warm temperatures, food (hydrocarbons and additives), and bacterial sources (dirt, air). Blockage of oil filters caused by water-in-oil emulsions stabilized by bacteria and fungus can occur. Maintenance programs to keep the oil clean and dry prevent bacterial growth. Circulating oil system designs that provide good oil flow and adequate drainage eliminate aerobic, stagnant pockets in which bacteria grow and degradation products accumulate.

The turbine oils according to DIN 51 515, part 1 are produced from highly refined, paraffinic base oils with good VT characteristics, with the addition of phenolic oxidation inhibitors and corrosion protection agents. The resistance to water entrainment is achieved by the addition of small amounts of surfactants. The additives present must not have a negative effect on air entrainment. Worldwide, uninhibited steam turbine oils are used only on a small scale, in Germany they have been abolished.

### 3. Water Turbine Oils

The thermal stress on hydro-turbine oils is small; however, it is important that they provide a good seal against water. Installations with large horizontal or vertical turbines are equipped with forced circulation lubrication and in most cases also with a separate oil circulation for the control unit. Normal engine oil raffinates with good oxidation stability and good adhesive properties are satisfactory for small turbines with collar step bearings, so that they cannot be displaced by water. High-quality lube oil raffinates with the appropriate viscosities can be used in hydroturbines with integrated control circuits; however, they do not satisfy the requirements with respect to corrosion protection and water shedding properties. Particularly the water shedding properties deteriorate with aging of the oils. Based on safety considerations, the expensive steam turbine oils are used also frequently for the lubrication of hydroturbines since they are better suited for the operation of turbines with circulation systems than normal lubricating oils. Due to the relatively low temperatures encountered, the oils must possess good cold properties. Oils with higher viscosities (ISO grades 100 or 150) are used for geared turbines and for the control units of Kaplan or propeller blade turbines (where this circuit is separated for technical reasons from the bearing oil circuit).