Lubricants and Lubrications

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Introduction

- **Lubrication is the reduction of friction to a minimum by replacing solid friction with fluid friction.**
- This is achieved by introducing an ideal film of oil or sufficient amount of grease to keep the two metal surfaces separated under the speeds and loads.
- The most important single factor that determines the effectiveness of the oil is the viscosity of the oil.

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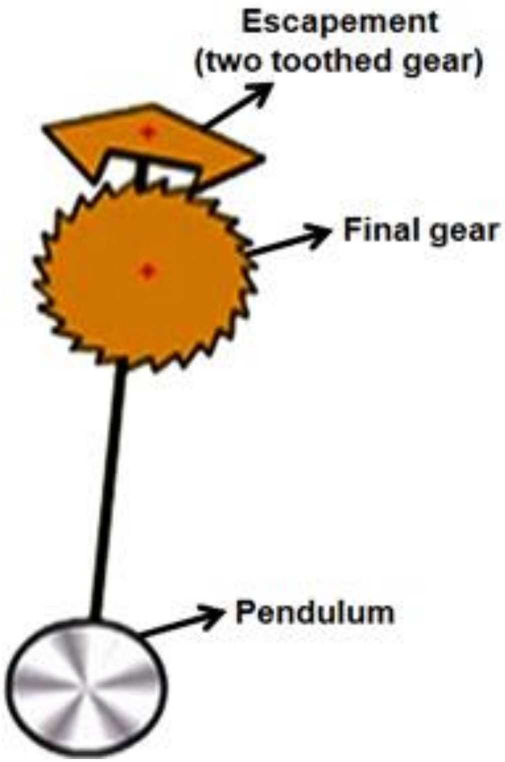

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Advantages of lubrication in addition to reducing friction and wear rate are :

- Reducing instant failures.

- Reducing fatigue failure (Lubricant reduces the force required in tangential direction so reduces the Fatigue Failure)

- Reducing surface failures.

- Reducing stress concentration.

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Applications of Lubricant :

1. Transmission parts.
2. Bearings.
3. Cams and followers.
4. Journals.
5. Seal faces.
6. Any situation involving metal to metal contact.

Expectations from Lubricants

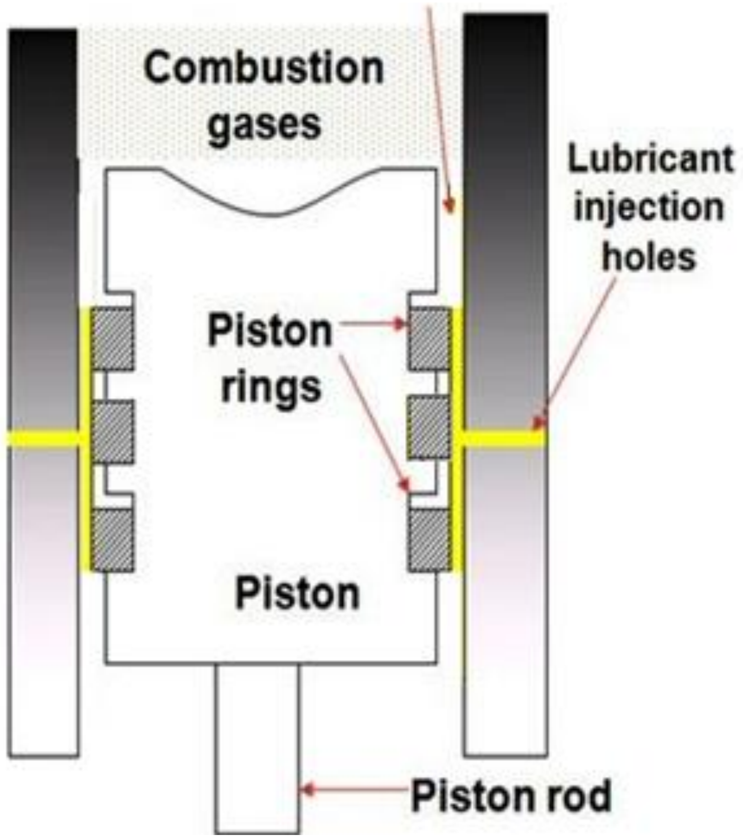
- **Example#1: Lubricant between cylinder liner and rings**
- Requirements are :

  • Lubricant must form a film to separate the surfaces and reduce the friction between metal to metal contact in order to improve the efficiency of the system.

  • Needs to adhere to the surfaces (attachment of thin lubricant layer on the surfaces).

  • Must neutralize the corrosive products of combustion.

  • Withstand high temperature inside the cylinder.



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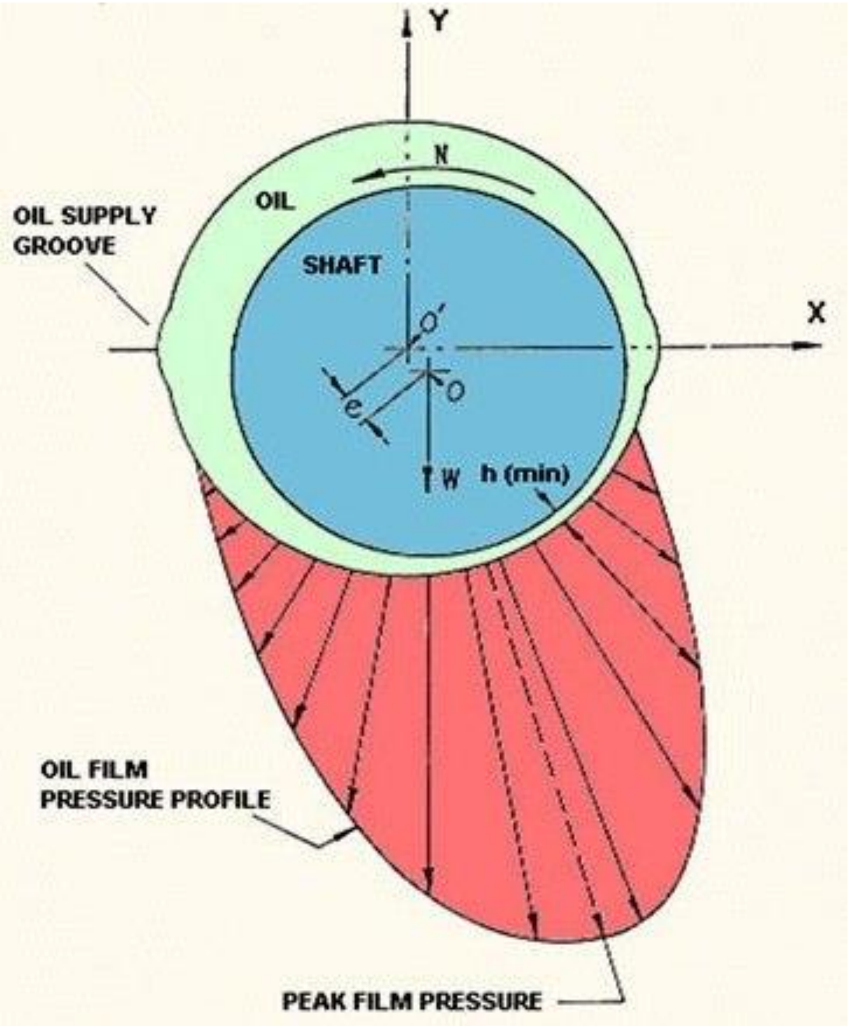
- **Example#1: Lubrication in journal bearings**
- Requirements are :

  - Lubricant should support heavy shaft and loads.

  - Lubricant should avoid contact stresses.

  - Lubricant should have ability to dampen vibrations.



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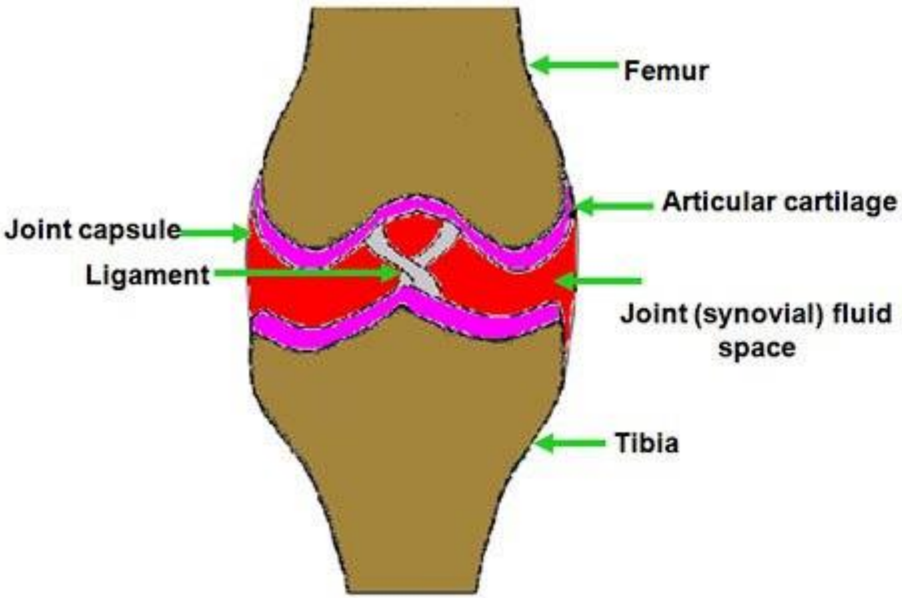
- **Example#3: Lubrication in bone joints**
- **Requirements are :**

  • Contain proteins that stick to cartilage layer resulting in smooth sliding.

  • Coefficient of friction ~ 0.01.

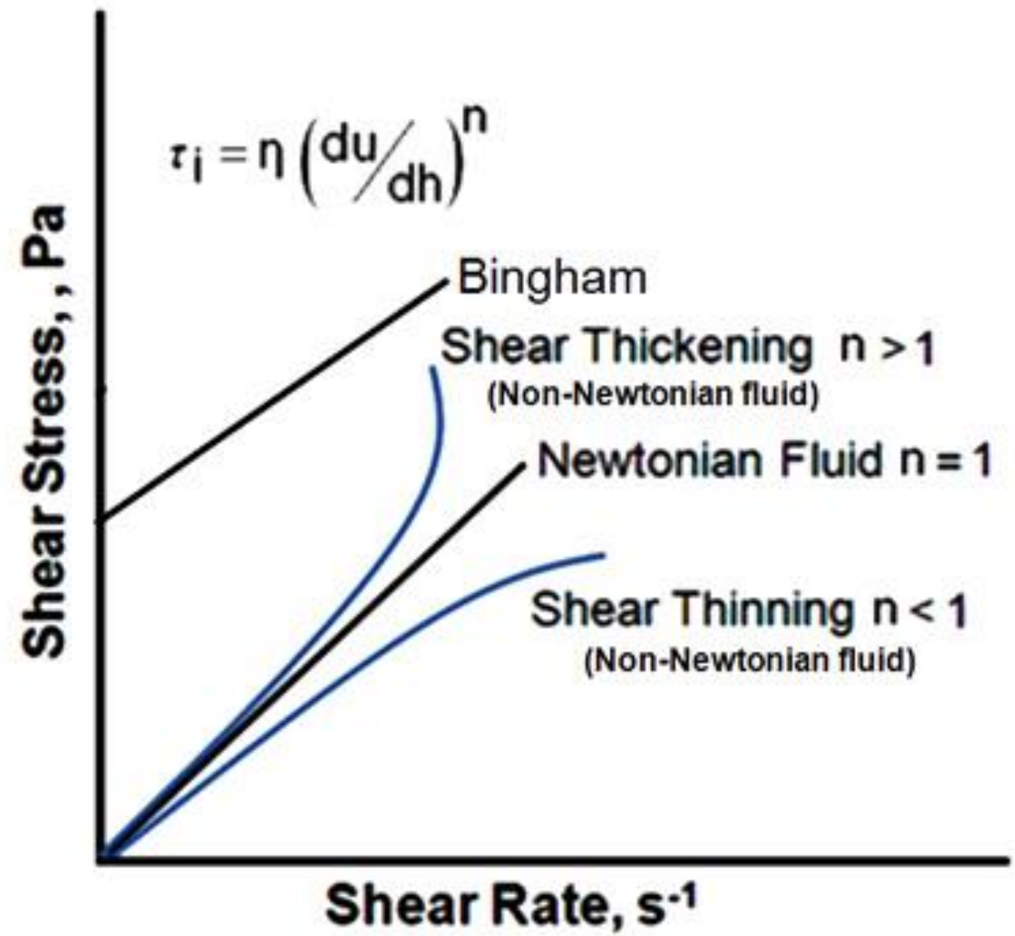
  • Minerals that nourish the cartilage cells.

  • Increase viscosity with increase in applied pressure.



Classification of Lubrications

- Lubricants are often classified as "Newtonian and "Non-Newtonian" fluids.
- This classification is on basis of relation between shear stress and shear strain rate



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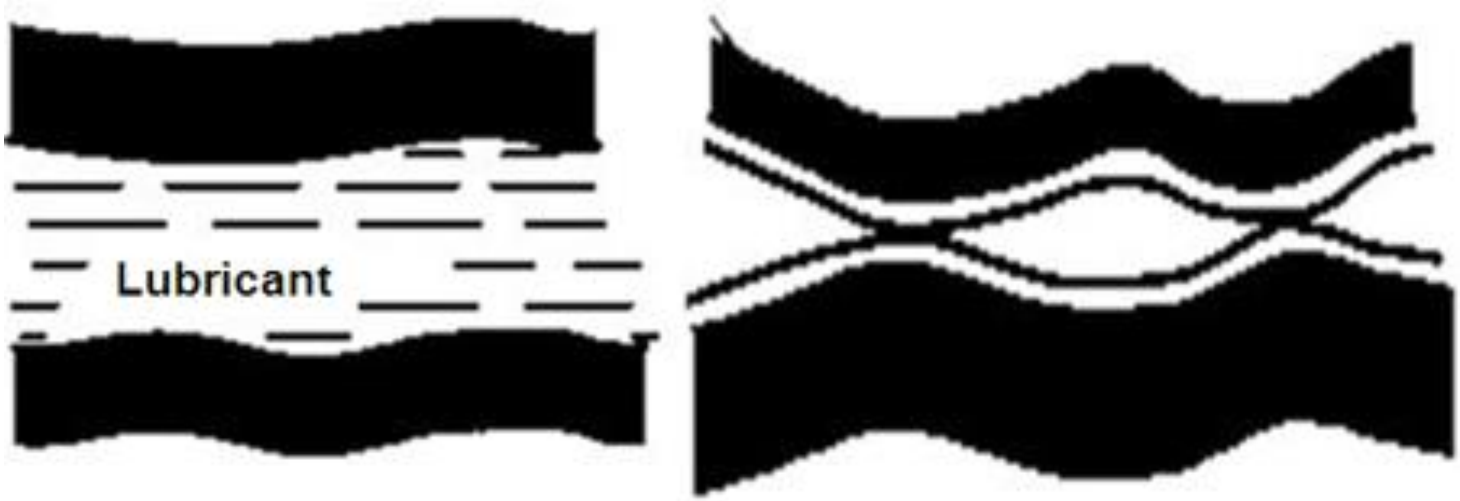
Types of Lubrication:

- Thick lubrication is governed by Reynolds theory. Thick lubrication is not advantageous because lesser the quantity of oil gives the lesser friction.

- Thin lubrication is far more complex. Requires scientific study at nano- to micro- level. From friction point of view, it is advantageous than thick lubrication.



(a) Thick Lubrication (b) Thin Lubrication

Specific Film Thickness

- Although fluid film lubrication relies heavily on fluid mechanics and kinematics, yet it is still a problem of two surfaces that are either in partial-contact or separated by a thin fluid film.
- Further, Reynolds equation that governs fluid film lubrication is based on the assumption of thin film. Therefore it is necessary to understand the importance of these lubrication mechanisms relative to the surface texture of tribo-pair.
- A dimensionless film parameter Λ (often referred as "specific film thickness") is used to classify the mentioned four lubricant regimes.

$$\Lambda = \frac{h_{\min}}{\sqrt{R_{rms,a}^2 + R_{rms,b}^2}}$$

$R_{rms,a}$ is root mean square (rms) surface roughness of surface a, and $R_{rms,b}$ is rms surface roughness of surface b.

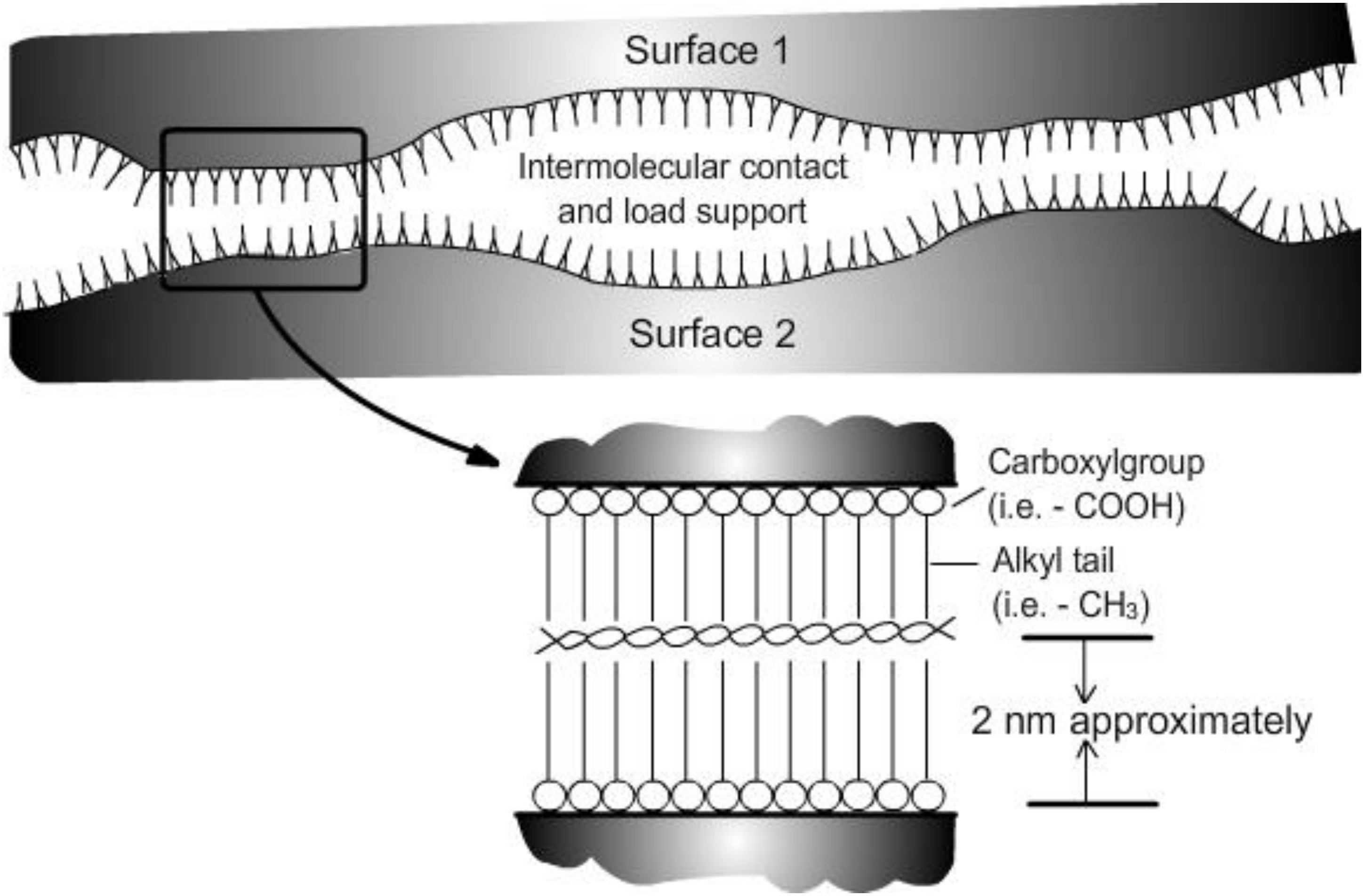
Classification of Lubrication Mechanisms

- Based on the value of dimensionless film parameter(Λ), lubrication mechanisms are classified as follows :

  - Boundary lubrication, $\Lambda < 1$
  - Hydrodynamic lubrication, $\Lambda > 5$
  - Mixed lubrication, $1 < \Lambda < 3$
  - Elasto-hydrodynamic, $3 < \Lambda < 5$

Boundary Lubrication

- 'Boundary Lubrication' - “Very thin adsorbed layers, about 10 A° thick, were sufficient to cause two glass surfaces to slide over each other”.
- The layer of lubricant separates sliding surfaces, i.e. no direct contact of the sliding parts.
- This situation is required for many applications such as steel gears, piston-rings and metal - working tools, to prevent severe wear or high coefficients of friction and seizure.



- The best boundary lubricants are long chain molecules with an active end group, typically fatty acids. Representative molecules of these types are shown in Fig. These consist of a hydrocarbon backbone of carbon atoms and an active end group. In fatty acid active group is COOH, known as the carboxyl group. Such a material, dissolved in a mineral oil, meets a metal or other solid surface with active end group attaches itself to the solid and gradually builds up a surface layer.

Mechanisms of Boundary Lubrication

- Boundary lubrication comprises of two mechanisms :

  (1) Physisorption.

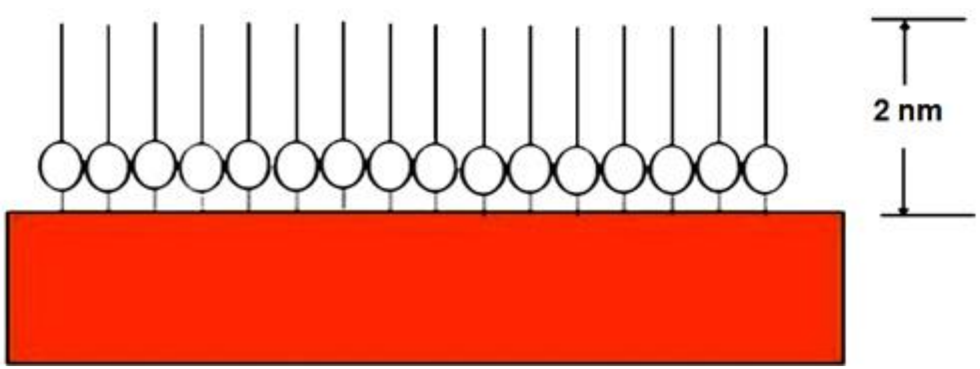
  (2) Chemisorption.

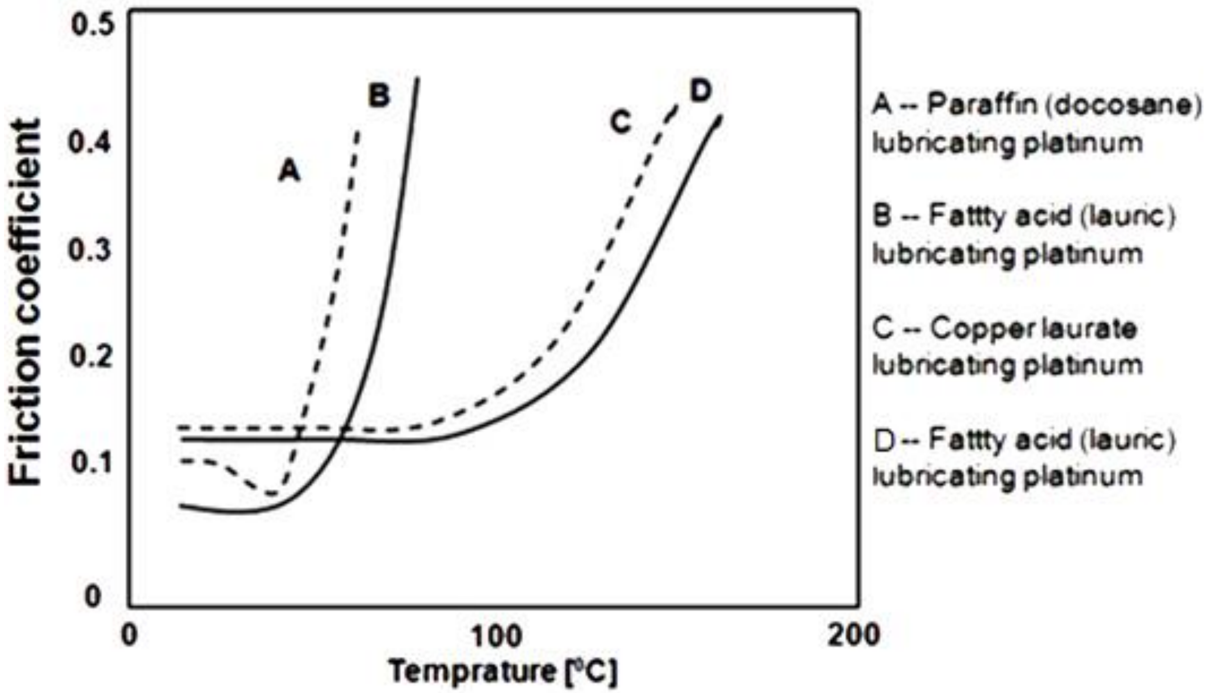
- **<u>Physisorption :</u>** First boundary lubrication mechanism is physisorption or "physical adsorption' (physical bonding by van der Waals force). In this mechanism, surface active molecules of oiliness additives are attracted to surface by electrostatic (dipole) forces(Fig)

- Energy is lowered when the molecules adsorb on the surface by physical attraction of additives on the surfaces. It requires some properties like

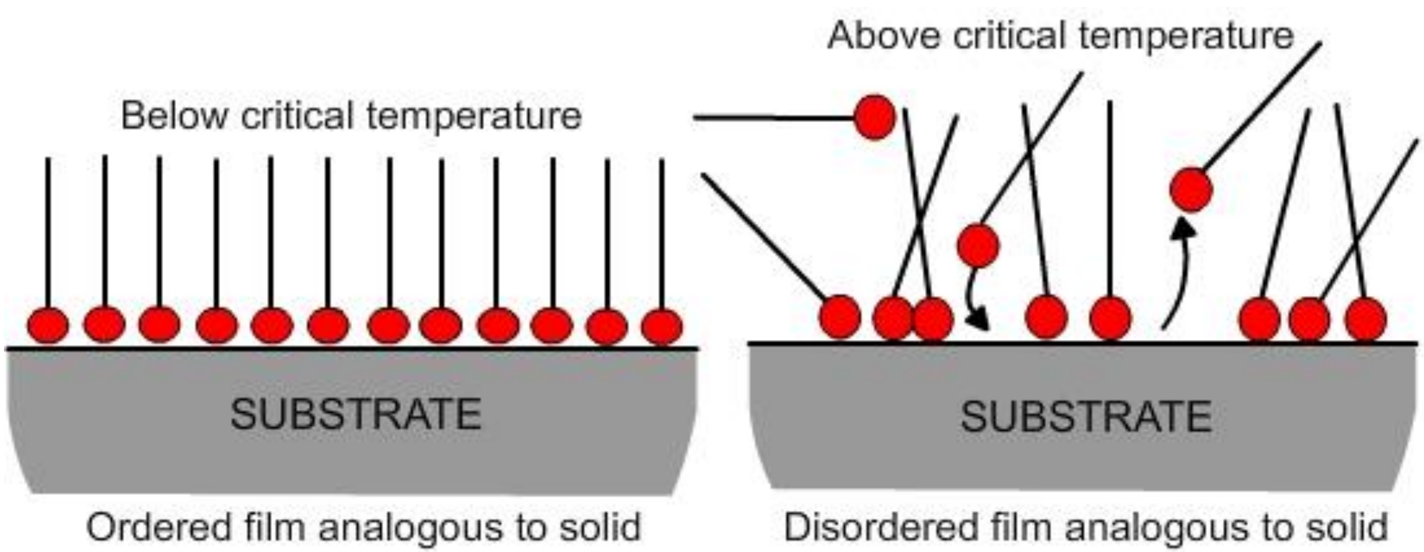
(i) Additives should dissolve in solute.

(ii) Attachment and detachment is a process encouraged by dilute concentrations and hindered by high concentration of polar molecules. Hence too much of additives should not be present..





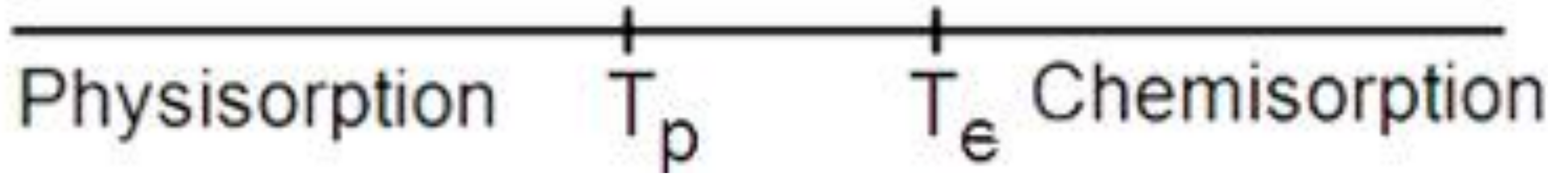
As the temperature increases, the viscosity reduces so that friction reduces . But as the temperature reaches critical value the friction increases, this is shown in Figs. indicates disruption of boundary lubricants at critical temperature, which results in increase in friction coefficient(Fig.



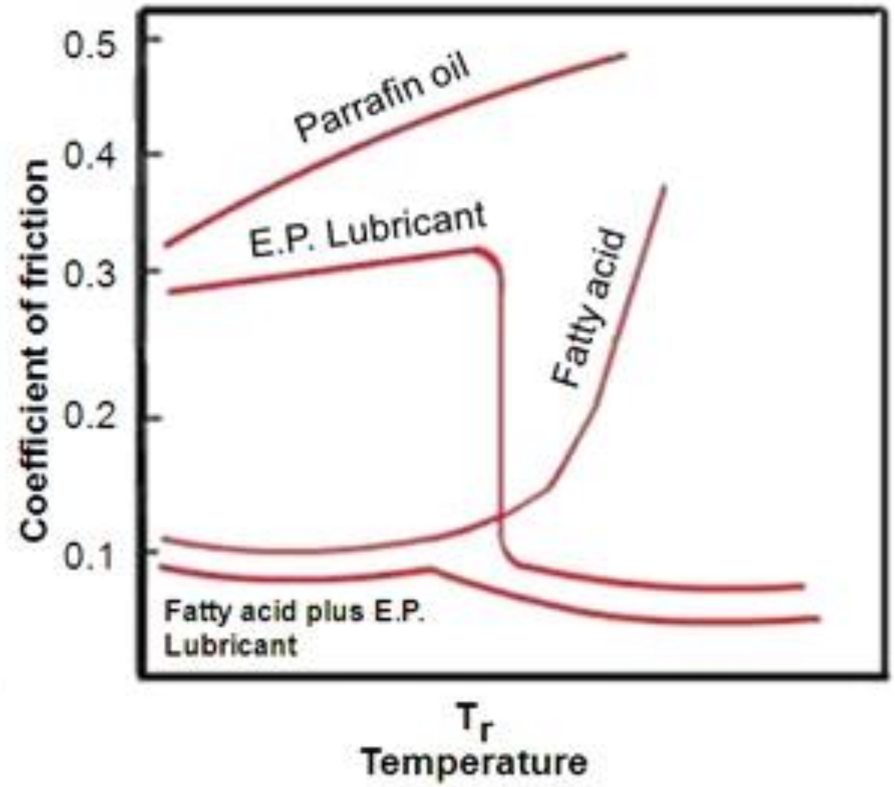
Chemisorption :

- Chemisorption is a form of corrosion. To form a chemically bound layer, three things are needed :

  - Chemically active group.
  - Reactive surface of material.
  - Surface free from physisorbed material so that chemical reaction occurs. This creates a gap(Fig.), where boundary additives become ineffective.



- During each contact, the chemical layer is rubbed off the surface and has to be reformed before next contact come round. Surface is therefore, slowly worn away so the additive must be chosen with care. Fig. indicates effective boundary lubrication requires a combination of physisorption and chemisorption.



Desirable properties from a boundary lubricant:

- • Dissolvability in lubricating oils.

  • Reactivity with metals at high temperature to form the metal soap (higher melting points).

  • Low shear strength to give a low friction.

  • High melting point so that it provides solid-film protection up to a high temperature.

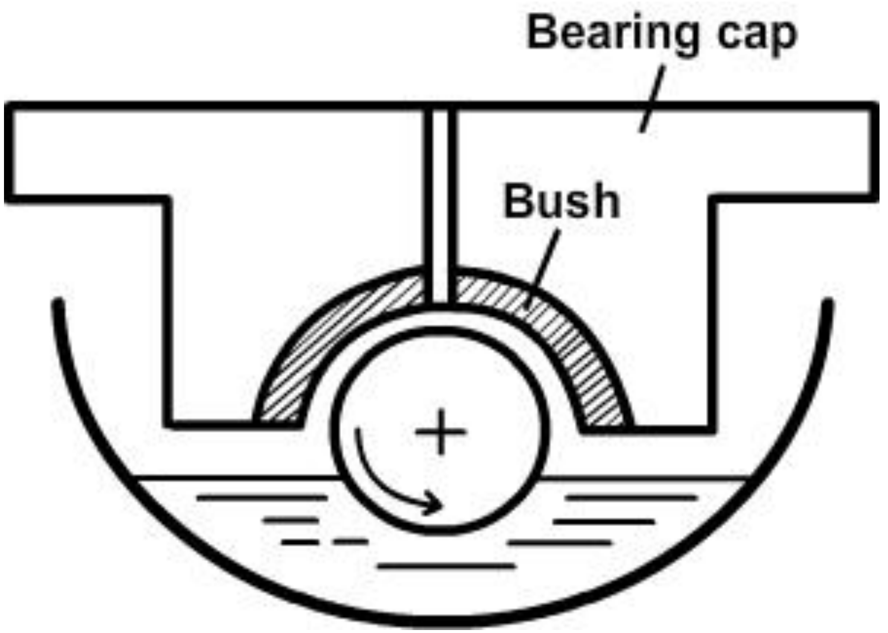
  • Resist penetration by surface asperities.

Hydrodynamic lubrication

- Hydrodynamic lubrication occurs if tribo-surfaces are perfectly rigid and retained their geometric shape during operation.
- This mechanism is extensively used to support load without causing any wear of machine components.
- In this mechanism, fluid completely separates relatively moving surface. The fluid may be liquid or gas. In case gas as separating fluid, lubrication mechanism is termed as aerodynamic lubrication.

Towers experiments

- Tower performed experiments on a partial arc bearing by imposing load using bearing cap on rotating journal as shown in the Fig. Lower part of journal was immersed in lubricating oil and friction resistance on bearing was obtained by measuring friction moment acting on bearing cap. He found reduction in the coefficient of friction in presence of liquid lubricants in rotation.



Conclusions based on Tower's experiments :

- (1) In oil bath lubrication, friction resistance follows the laws of "liquid friction" compared to "solid friction (coulomb, adhesion)".

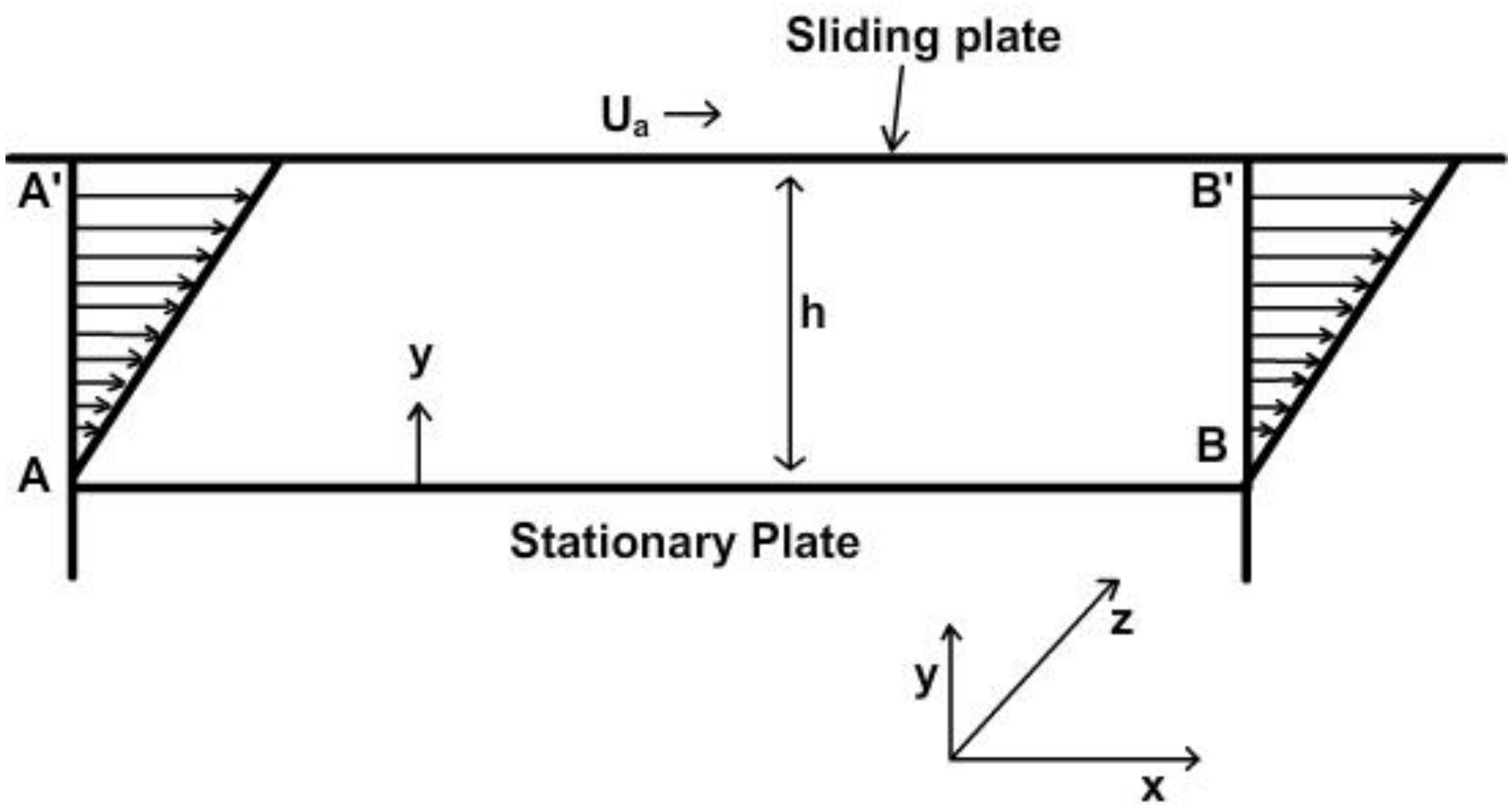
  (2) Floating is possible, when we use lubricating oil.

  (3) Fluid pressure is maximum in middle of bush and it is more than double the mean pressure. It means pressure is not constant but varying.

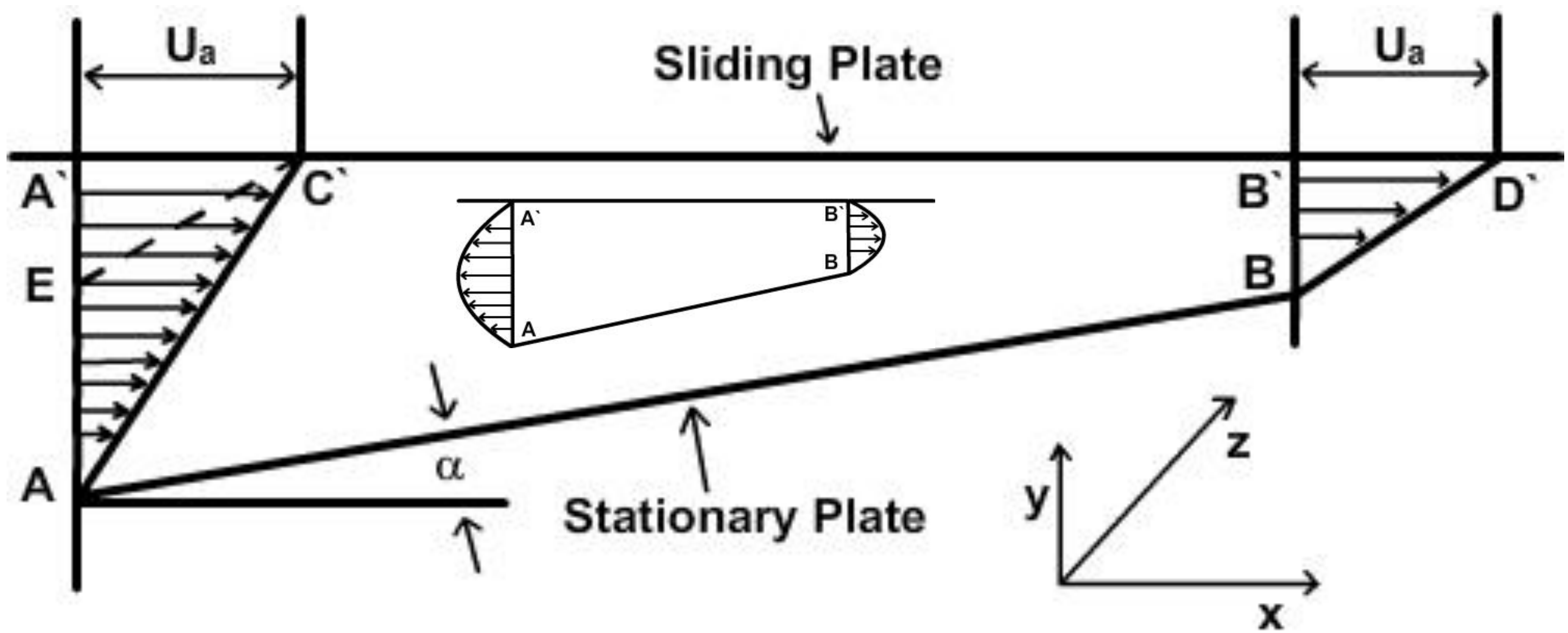
  (4) Unstable friction resistance occurs during lubrication other than oil bath lubrication, probably due to insufficient amount of oil.

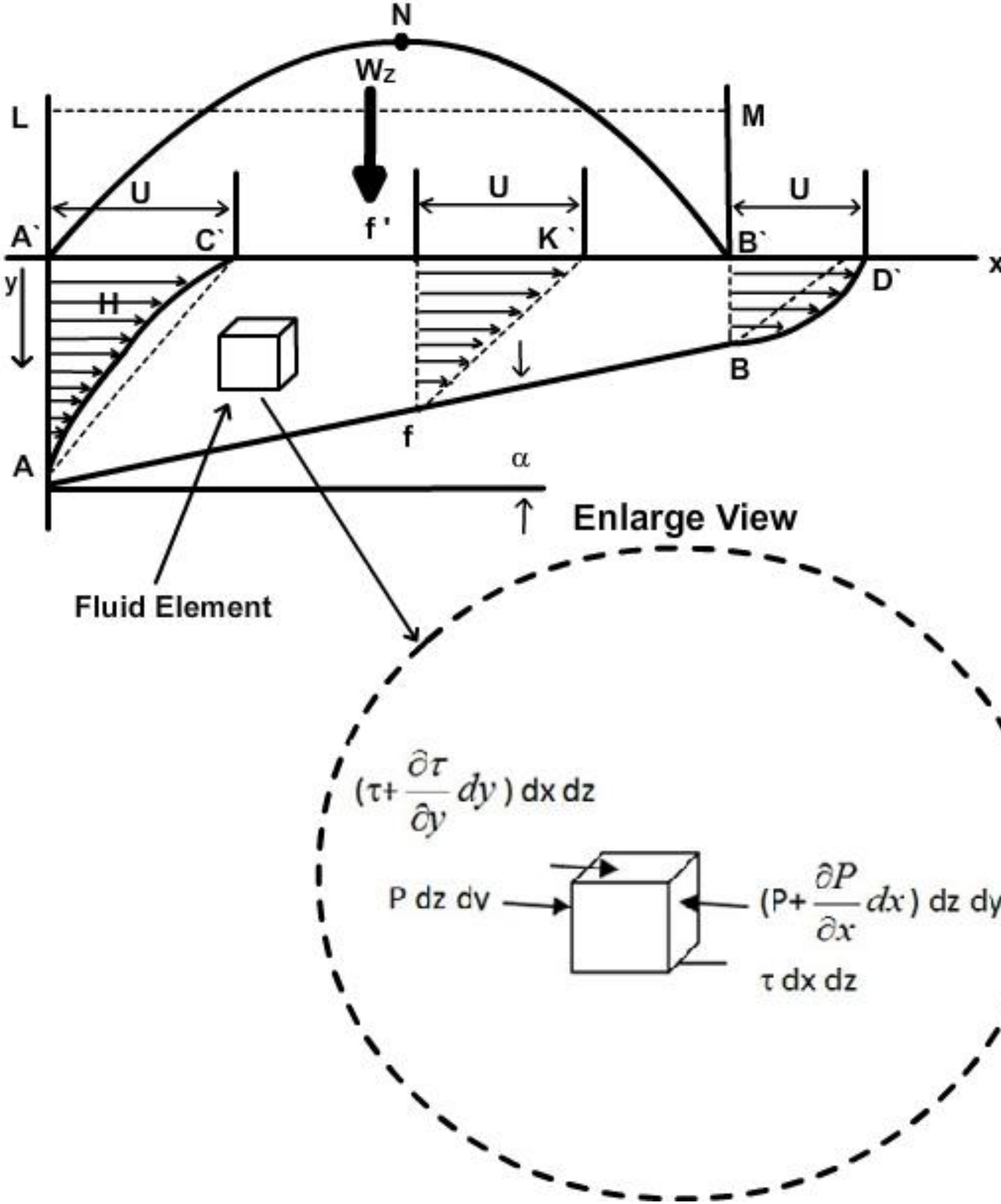
  (5) Tower's experimental results motivated researchers to understand the effect of various parameters responsible for generation of fluid film pressure.

- To understand the Tower's experiment, we can take an example of parallel plate (Fig.) and use fluid mechanics concepts
- Consider two parallel plates, AB and A’ B’, separated by fluid film of thickness h in y-direction. Assume plate A’ B’, is sliding at velocity u_a relative to plate AB. No pressure will develop within the parallel surfaces.



- Now assume plate AB is inclined at angle α and film thickness h is function of coordinate x. Due to inclination exit area (B B') will be smaller compared to entrance area (A A') as shown in Fig.
- To conserve the mass flow rate, a positive pressure gradient will be generated at exit and negative pressure gradient will generated at entrance as shown in Fig.

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Fluid Element
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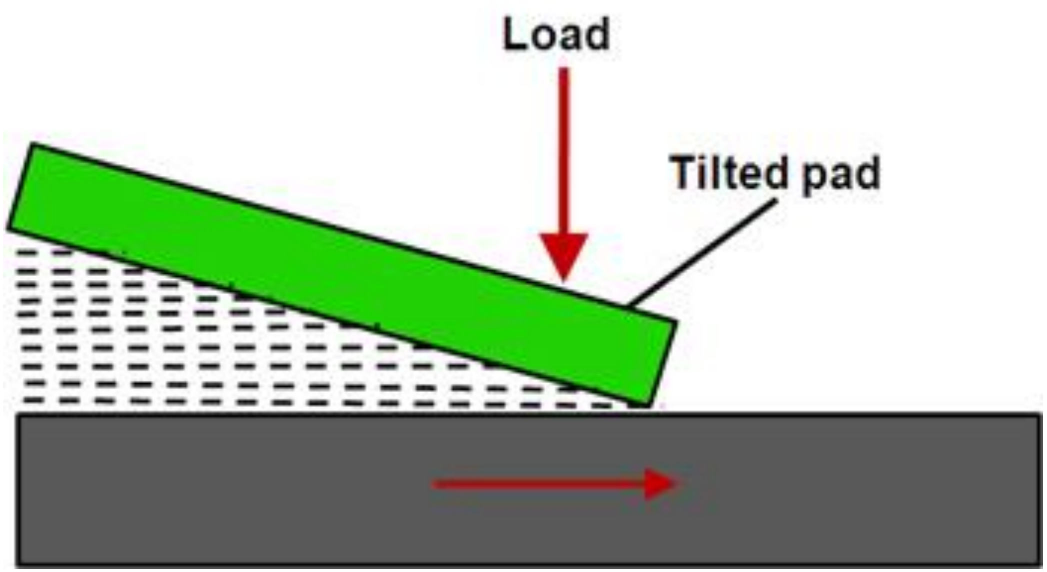
(P+ ∂P/∂x dx) dz dy
τ dx dz

- To develop hydrodynamic lubrication mechanism, two features are essential :

  (1) The liquid must be viscous.

  (2) The geometry of the surfaces must be such that as one surface moves over the other and they must produce a convergent wedge of liquid as shown in Fig.



Characteristics features of hydrodynamic lubrication :

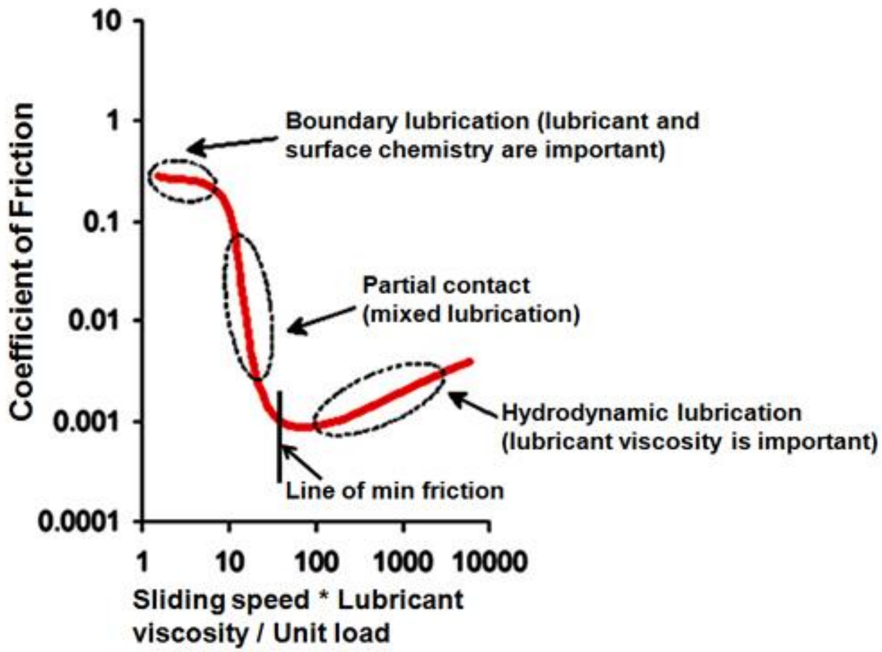
(1) In hydrodynamic lubrication, the total friction arises from shearing of the lubricant film so that it is determined by the viscosity of the oil.

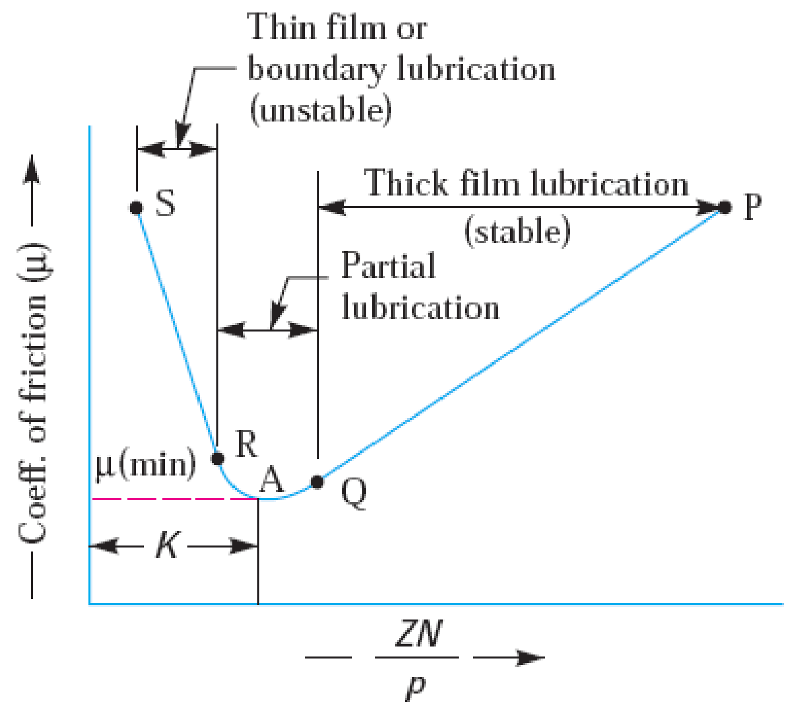
We can observe that, lower the viscosity of the oil, the lower the friction. However, the distance of nearest approach (minimum film thickness) between sliding surfaces places a limit to the lowest possible viscosity.

(1) The great advantages of hydrodynamic lubrication are that the friction can be very low ($\mu \sim 0.001$) and, in the ideal case, there is no wear of the moving parts.

Mixed Lubrication

- In bearings and other lubricated devices where relative motion occurs, lubrication is divided into three types : **fluid film**, wherein the load is supported by the film pressure of a fluid lubricant; **boundary**, in which the load is supported by direct surface films of the moving solid members; and **mixed**, where the load is carried by some mixture of the first two. All three lubrication mechanisms can be compared using stribeck curve.





- The minimum amount of friction occurs at *A and at this point the* value of *ZN / p is known as* ***bearing modulus which is denoted by K.*** The bearing should not be operated at this value of bearing modulus, because a slight decrease in speed or slight increase in pressure will break the oil film and make the journal to operate with metal to metal contact.
- This will result in high friction, wear and heating. In order to prevent such conditions, the bearing should be designed for a value of *ZN / p at least three times* the minimum value of bearing modulus (*K). If the* bearing is subjected to large fluctuations of load and heavy impacts, the value of *ZN / p = 15 K may* be used.
- From above, it is concluded that when the value of *ZN / p is greater than K, then the bearing* will operate with thick film lubrication or under hydrodynamic conditions. On the other hand, when the value of *ZN / p is less than K, then the oil film* will rupture and there is a metal to metal contact.

- Fig. shows two machine elements in lubricating contacts.
- These are four possible mechanisms; asperities in contact may experience dry or boundary lubrication and asperities in contact with liquid lubricant may experience elasto-hydrodynamic or hydrodynamic lubrication.

- W_1 load carried by dry(no intended lubrication).

  W_2 load carried by boundary lubrication (Physical/chemical lubrication).

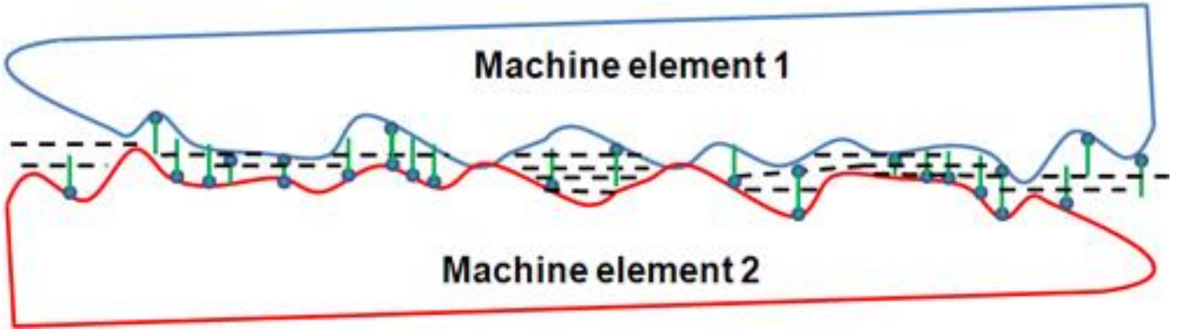
  W_3 load carried by elasto-hydrodynamic lubrication.

  W_4 load carried by fluid Lubrication.

  $\omega_1 + \omega_2 + \omega_3 + \omega_4 = 1.0$

  ω_1, ω_2, ω_3 and ω_4 are the weights given to the different lubrication mechanism, and sum of all weights must be equal to one.

  Total load capacity $W = \omega_1 W_1 + \omega_2 W_2 + \omega_3 W_3 + \omega_4 W_4$



Mixed Lubrication : Wear

- he complexity of the wear processes, prevents real testing of the concept based on superposition of individual components of wear, which is often expressed by Eq.

$$V = v_a + v_c + v_f + v_{af} + v_{cf} + v_{abrasion}$$

- Where V is the wear volume , and the subscripts f, a, c, refer to fatigue, adhesion, corrosion respectively. There is a recognition that some of the mechanisms are interactive, therefore V_{af} indicates wear volume from fatigue and adhesion combined. In the above equation, abrasion has a unique role; since all of the mathematical models for primary wear assume clean parts and lubricant, there will be no abrasion until wear particles have accumulated. Therefore, V abrasion becomes a function of v_a, v_c and v_f, probably a step function. In most cases V_{af} is negligible because adhesion and fatigue rarely coexist. However, corrosion is known to accelerate fatigue, therefore, V_{cf} may be significant.

- It has been observed that the sensitivity of wear reduction in the presence of boundary lubricant is higher than reduction in friction coefficient.

Elasto-Hydrodynamic Lubrication

- In rolling contact elements (bearings, gears), generated fluid film is slightly greater than irregularities of the surfaces, but serve much longer than predicted by mixed lubrication theories.
- Increased viscosity under the action of extreme local pressure leads the generation of thicker film.
- Many times classical hydrodynamic lubrication theory predicts a negligible fluid film in high-pressure non-conforming contacts such as exist in rolling element bearings and gears, but on considering the influence of pressure on both elastic deformation and lubricant viscosity, a significant oil-film thickness becomes possible.
- It is interesting to note this difference between elasto-hydrodynamic lubrication(EHD) and hydrodynamic lubrication(HD) occurs as HD is based on the assumption of a fluid continuum , while EHD shows significant increase in local (limited to few molecular thickness) viscosity compared to bulk viscosity.

Barus Relation

- According to the Barus relation, lubricant viscosity increases with pressure.

  Barus Relationship: **$\eta = \eta_0 \exp(\alpha p)$**

  where

  η = fluid viscosity at pressure p.

  η_0 = fluid viscosity at ambient pressure.

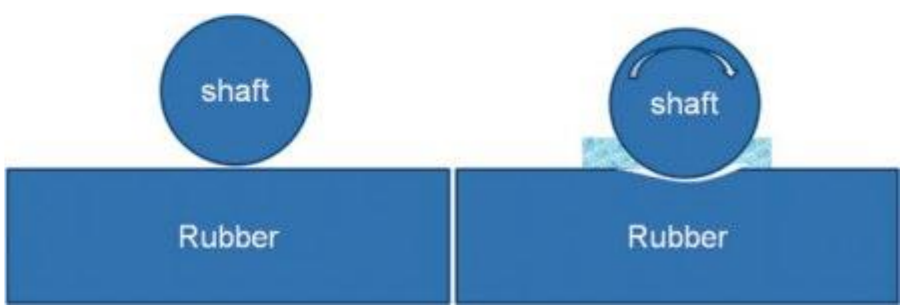
  α = piezo-viscous coefficient.

  α for oil ~ 1 - 2 * 10^{-8}/pa

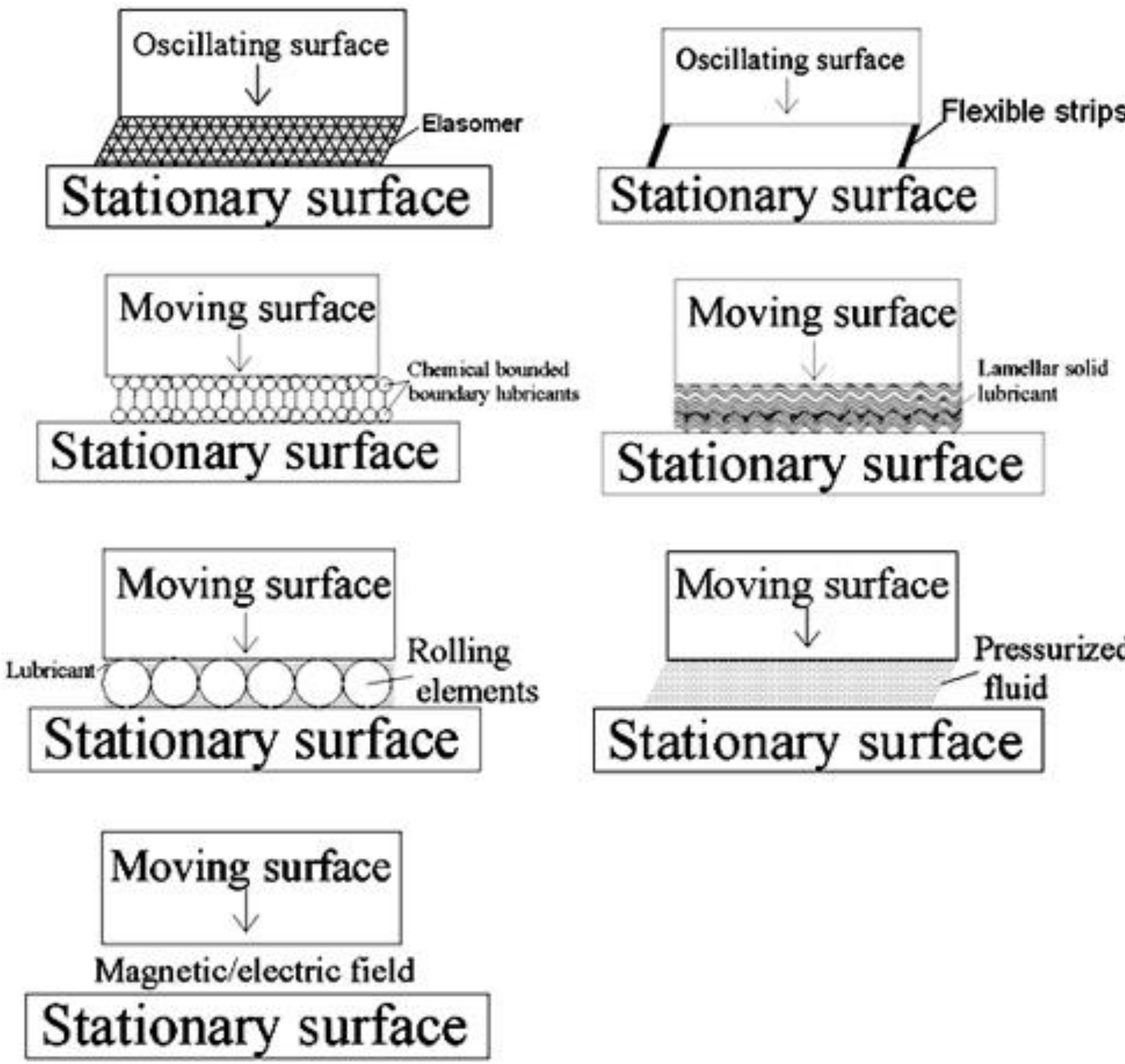
- At high pressure, the molecules take considerable time to re-arrange themselves, following pressure change. This means viscosity thickening takes sometime, and it does not happen instantaneously.

- In addition to viscosity thickening under mechanical load, every surface gets deform. The applied lubricant gets dragged into the interface and builds pressure. For example; rubber seals, gear teeth. Film pressure is greater than 10 MPa is sufficient to deform the tribo-surfaces by sub-micron to micron level. Fig. shows elastic deformation of rubber under load. On relative motion, lubricant is dragged and builds pressure and supports more load.
- In other words, three mechanisms help to support the load under elasto-hydrodynamic lubrication.

  - Elastic deformation of tribo-surfaces.
  - Effect of increase in viscosity with pressure.
  - Hydrodynamic lubrication.



Various concepts to separate two solid surfaces.

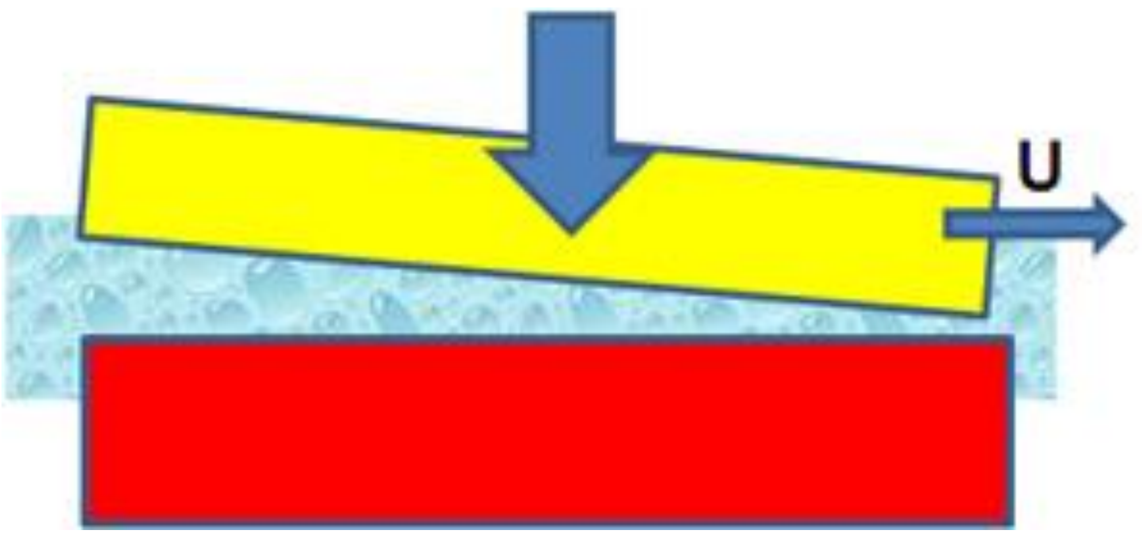


Fluid is defined as a substance that easily moves and changes its relative position without a separation from the bulk mass. Fluid includes all gases, liquids and easy flowing solids

Various Fluid Films

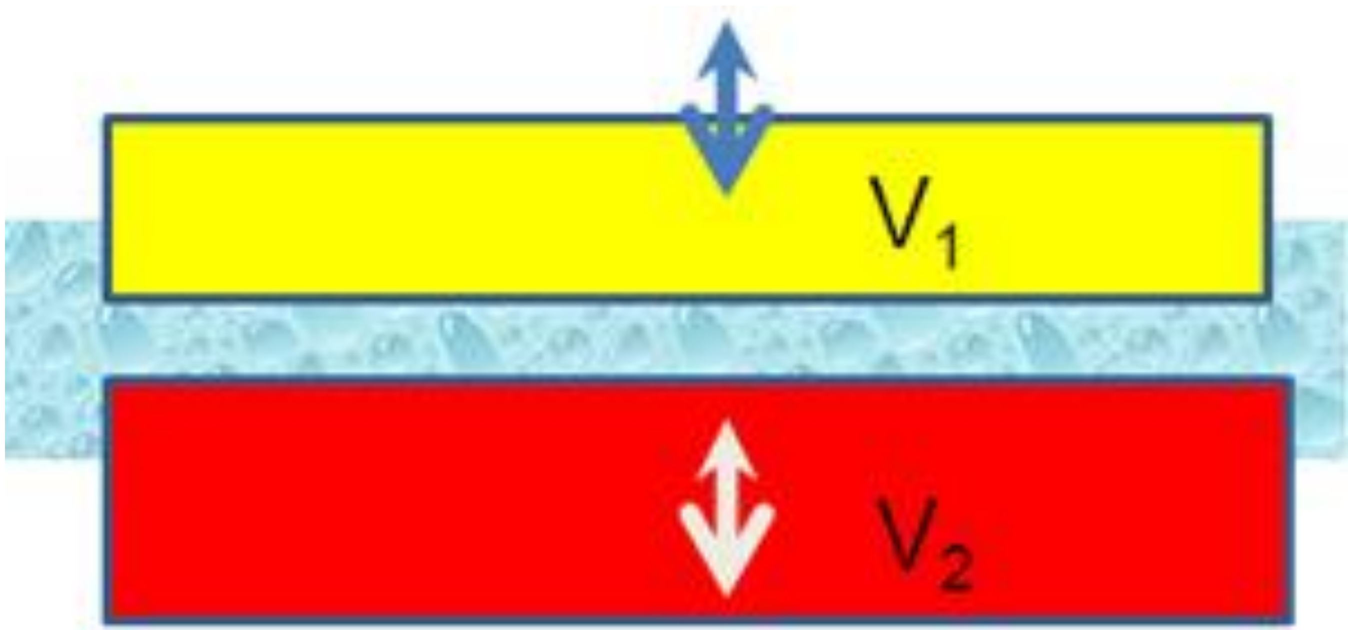
Hydrodynamic (Aerodynamic) :

- Converging wedge shaped geometry; as shown in Fig. is essential for this lubrication.
- Viscosity of lubricant plays an important role to support the load.



Squeeze Film :

- Load and/or speed variation generate squeeze film action.
- Viscosity of lubricant plays important role.



Hydrostatic (Aerostatic) :

- External pressure of fluid needs to be supplied to generate hydrostatic/aerostatic lubrication.
- Independent or to support hydrodynamic lubrication.