Chapter 1 Questions?

1. **What are Types of Viscometers**

   **Rotational Viscometer**
   
   This is perhaps the only type of viscometer which measures the absolute viscosity of oil. It is in the form of two concentric cylinders of which one rotates in the oil whose viscosity is to be measured (Fig. 2.2). This apparatus is known as the Couette-Hatscheck viscometer. When one of the cylinders rotates, the motion of oil between the cylinders is similar to that of flow of liquid between two parallel plates. However, the effect of curvature can affect the result to some degree. From the measurement of the frictional drag due to viscous shear on the inner cylinder at a particular velocity it is possible to calculate the absolute viscosity. This viscometer is suitable for measuring viscosities of oils having relatively high viscosity. This instrument is usually calibrated with fluids of known viscosity and the viscosities of test samples are taken from the calibration chart.

   **Fig. 2.2: Basic arrangement of rotational viscometer**

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**Capillary Viscometer**

In capillary viscometer a direct measurement of absolute viscosity is not possible. Here kinematic viscosity is measured. The test oil is allowed to flow through a capillary tube of known dimensions. According to Eq. (2.10) the kinematic viscosity will be some function of time required
for a given volume of liquid to flow through the tube. The
sketch of one such viscometer is shown in Fig. 2.3.
From Eq. (2.10)

\[ v = C t \quad (2.11) \]

where \( C = \frac{\pi g H R^4}{8 \nu L} \), a constant for a given viscometer. By
using some liquid of known viscosity and density, like distilled
water, sugar solution, the time required for a given volume to
flow through the capillary is determined and the constant for
the instrument is found.

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**Falling Sphere Viscometer**

If a sphere is falling through a viscous liquid under a
constant force, it will assume a constant velocity. Stokes
formula can be applied for a sphere moving through an
infinite fluid. A sphere falling freely under gravity in liquid
will be attaining a velocity \( v \) given by

\[ v = \frac{2 R^2 (\rho - \rho') g}{9 \eta} \quad (2.12) \]

where \( R \) is the radius of the sphere and \( \rho \) and \( \rho' \) are the
densities of sphere material and liquid, respectively. In Fig.
2.5 a sketch of a falling sphere viscometer is shown. A
sphere from the top of a vertical tube containing oil is
released. The time \( t \) taken for the falling body to cover a
measured distance \( H \) is recorded by an electronic clock.
Knowing the velocity \( v \) \((= H/t)\) and using Eq. (2.12), the
viscosity can be computed.

As Stokes formula given by Eq (2.12) is true for infinite fluid, a suitable correction factor \( cf \) to
Eq. (2.12) is sometimes necessary to account for the finite tube diameter. Eq. (2.12) then can be
modified as

\[ \eta = \frac{2 R^2 (\rho - \rho') g}{9 \nu \cdot cf} \quad (2.13) \]

An approximate value of \( cf \) given by

\[ \text{cf} = 1 - 2.104 \ (d/D) + 2.09 \ (d/D)^3 - 0.9 \ (d/D)^5 \]

may be used. Here \( d \) and \( D \) are diameter of
sphere and internal diameter of the tube.
Efflux Viscometer

There exist three standard instruments of the efflux type. These are the Redwood, Engler and Saybolt Universal known, respectively, in Great Britain, Europe and the U.S.A. In each case the time taken for a given volume of oil to flow through an orifice (or jet) is a measure of viscosity (Fig. 2.4). Here the viscosity is expressed either in Redwood second or Engler second or Saybolt Universal second depending on the type of instrument used. A conversion table of Redwood second to kinematic viscosity (in centistoke) is then to be used in the case of Redwood viscometer. The flow of liquid here does not obey Poiseuilli's law. One has to take the help of a chart for conversion of second to centistoke. Data for conversion of Redwood and Saybolt units to kinematic viscosity are found in\(^1\). It should be remembered that these tables are approximate. Relatively large samples of oil (50 c.c. or more) are required for the test. Redwood viscometer No. 1 shown in Fig. 2.4 is used for oils having viscosity up to 500 cS and No. 2 for higher viscosities.

![Diagram of Redwood No. 1 Viscometer](image)

**Fig. 2.4:** Redwood No. 1 Viscometer

- A. Oil cup
- B. Levelling wire
- C. Copper bath
- D. Tap
- E. Heating tube
- H. Stirrer
- J. Agate jet
- K. Stirrer handle
- R. Standard
- S. Thermometer clip
- \(T_1\) & \(T_2\) Thermometers
- V. Ball valve
2. What is viscosity and what are different parameters that affect the viscosity of a fluid

Dynamic Viscosity

Consider two flat surfaces separated by a film of fluid of thickness \( h \) as shown in Figure 2.1. The force required to move the upper surface is proportional to the wetted area \( A \) and the velocity gradient \( \frac{\Delta u}{h} \), as the individual fluid layer in a thicker film will be subjected to less shear than in a thin film, i.e.:

\[
F \propto A \times \frac{\Delta u}{h}
\]  
(2.1)

This relationship is maintained for most fluids. Different fluids will exhibit a different proportionality constant \( \eta \), called the ‘dynamic viscosity’. The relationship (2.1) can be written as:

\[
F = \eta \times A \times \frac{\Delta u}{h}
\]  
(2.2)

Rearranging gives:

\[
\eta = \frac{F/A}{\Delta u/h}
\]  
or

\[
\eta = \frac{\tau}{\Delta u/h}
\]  
(2.3)

where:
- \( \eta \) is the dynamic viscosity [Pa·s];
- \( \tau \) is the shear stress acting on the fluid [Pa];
- \( \Delta u/h \) is the shear rate, i.e., velocity gradient normal to the shear stress [s⁻¹].

Before the introduction of the SI system the most commonly used dynamic viscosity unit was the Poise. Incidentally this name originated not from an engineer but from a French medical doctor, Poiseuille, who studied the flow of blood. For practical applications the Poise [P] was far too large, thus a smaller unit, the centipoise [cP], was more commonly used. The SI unit for dynamic viscosity is Pascal-second [Pa·s]. The relationship between Poise and Pascal-second is as follows:

\[
1 \, \text{[P]} = 100 \, \text{[cP]} = 0.1 \, \text{[Pa·s]}
\]

Kinematic Viscosity

Kinematic viscosity is defined as the ratio of dynamic viscosity to fluid density:

\[
u = \frac{\eta}{\rho}
\]  
(2.4)

where:
- \( \nu \) is the kinematic viscosity [m²/s];
- \( \eta \) is the dynamic viscosity [Pa·s];
- \( \rho \) is the fluid density [kg/m³].

Before the introduction of the SI system the most commonly used kinematic viscosity unit was the Stoke [S]. This unit, however, was often too large for practical applications, thus a smaller unit, the centistoke [cS], was used. The SI unit for kinematic viscosity is [m²/s], i.e.:
3. **Explain in detail the variation of viscosity with respect to temperature and pressure?**

   Temperature effect is discussed earlier in question 3

   **Effect of pressure.**

   As the pressure is increased the molecules are forced to come closer, thereby increasing the intermolecular forces. This increases the viscosity. At low pressure the difference is small, but at high pressure it is significant.

   Lubricant viscosity increases with pressure. For most lubricants this effect is considerably larger than the effect of temperature or shear when the pressure is significantly above atmospheric. This is of particular importance in the lubrication of heavily loaded concentrated contacts, which can be found, for example, in rolling contact bearings and gears. The pressures encountered in these contacts can be so high and the rate of pressure rise so rapid that the lubricant behaves like a solid rather than a liquid. This is very important in the case of elasto hydrodynamic line and point contacts such as cam gears, rolling element bearings. It is quite difficult to have a single equation to express the variation of viscosity with pressure.

4. **Explain in detail the variation of viscosity with shear rate?**

   Viscosity of fluids varies as a function of shear rate and the branch of study dealing with this is known as **fluid rheology**. A fluid that follows Eq. (10.2) is called a Newtonian fluid. In case of non-Newtonian fluids, viscosities vary with shear rate. Liquids with loose molecular structure such as water behave as Newtonian. Shear thinning (a phenomenon of thinning of fluid with increase in shear rate) occurs in case of so-called pseudo-plastic fluids. These fluids are generally composed of long molecules randomly oriented with no connecting structure. When shear stress is applied, the molecules tend to get aligned resulting in a reduction in viscosity. In dilatant fluids, shear thickening occurs, i.e., the fluid gets thickened with an increase in the shear stress. These fluids are usually suspensions having high-solid content. For Bingham plastic fluids, some shear stress is required before the flow begins and these fluids usually possess a three-dimensional structure that can resist a certain amount of shear stress known as **yield stress**. Many greases act like Bingham fluids. When, for a material, viscosity depends on its previous shearing history, it is termed as thixotropic material. All solid and liquid polymers behave as thixotropic material to some extent. Figure 10.5 shows schematic curves for dependence of shear stress and viscosity on shear rate for different fluids.

   A large number of liquids become non-Newtonian at high-shear rates. Above a certain shear rate viscosity starts decreasing and the fluid behaves as non-Newtonian. This is known as **shear thinning**. A drop in viscosity also occurs due to thermal thinning.
5. **Explain the phenomena of decrease of viscosity of oil with increase in temperature**

Viscosity of oils is mainly due to intermolecular forces. With increasing temperature, liquid starts expanding, the molecules move farther apart and the intermolecular forces decrease, resulting in the viscosity decreasing. Thus the viscosity of lubricating oils decreases with increasing temperatures. The decrease in viscosity for different oils for the same temperatures increase will be different. Hence two oils having the same viscosity at some temperature may have different viscosities at different temperatures.

Viscosity index is defined for the same purpose.

6. **In general how many temperatures are needed to specify the viscosity of an oil and why**

Today in the market there are many oils and new oils are coming into market. Each oil will behave in its own manner depending upon the intermolecular forces. For some oils the Viscosity temperature relationship may be linear and for some it could be quadratic, exponential. So it is difficult to say how many viscosity values are required.

To fit a polynomial equation of order $n$, we require $n+1$ data points to accurately predict the variation.
If viscosity temperature relationship of the oil is linear we require two data points. If the relation is cubic we require at least four points. But in Viscosity measurements Vogel equation is widely used. It is most accurate. There are several viscosity-temperature equations available. Some of them are purely empirical while others are derived from theoretical models. The most accurate of these is the Vogel equation.

Three viscosity measurements at different temperatures for a specific oil are needed in order to determine the three constants in this equation. The oil viscosity can then be calculated at the required temperature, or the operating temperature can be calculated if the viscosity is known. Apart from being very accurate the Vogel equation is useful in numerical analysis.

\[\eta = Ae^{b/(T - c)}\]

Most accurate; very useful in engineering calculations

7. **Discuss the effect of Temperature on Viscosity index.**

Viscosity of the oils decreases with increase in temperature. The viscosity index is an entirely empirical parameter that compares the kinematic viscosity of the oil of interest to the viscosities of two reference oils that have a considerable difference in sensitivity of viscosity to temperature. The reference oils have been selected in such a way that one has a viscosity index equal to zero (VI=0) and the other has a viscosity index equal to one hundred (VI=100) at 100 deg F (37.8 deg C) but they both have the same viscosity as the oil of interest at 210 deg F (98.89 deg C) as illustrated in Figure 2.3. Since Pennsylvania and Gulf Coast oils have the same viscosity at 210 deg F (98.9 deg C) they were initially selected as reference oils. Oils made from Pennsylvania crude were assigned the viscosity index of 100 whereas oils made from the Gulf Coast crude the viscosity index of 0.

A high value of Viscosity index e.g. 100 means very less change in viscosity with temperature. A low value of Viscosity index e.g. 0 means very less change in viscosity with temperature.

In general to determine the viscosity index at a required temperature, viscosity is measured at the required temperature and at 100 deg C and VI is calculated from the following formula:

\[\text{VI} = \frac{(L - \text{viscosity at required temp})}{(L - H)} \times 100\]

L and H are values of equivalent viscosity corresponding to the viscosity of the oil at 100 deg C.

Note that the viscosity index is an inverse measure of the decline in oil viscosity with temperature. High values indicate that the oil shows less relative decline in viscosity with temperature. The viscosity index of most of the refined mineral oils available on the market is about 100, whereas multi grade and synthetic oils have higher viscosity indices of about 150.

For example to find the viscosity index of an oil that has a kinematic viscosity at 40 deg C of \(\nu_{40} = 135 \text{ cS}\) and at 100 deg C of \(\nu_{100} = 17 \text{ cS}\).

With the above data refer to standard tables for \(\nu_{100} = 17 \text{ cS}\), and from the table determine the value of \(L\) and \(H\). \(L = 369.4\) and \(H = 180.2\) can be found. Substituting these values into the viscosity index equation yields:

\[\text{VI} = \frac{(369.4 - 135)}{(369.4 - 180.2)} \times 100 = 123.9\]

We know the viscosity decreases with increase in temperature.
Let us consider the viscosity of oil increased to 50 deg C is 150 cs
Hence VI at 50 degC = \((369.4 - 150) / (369.4 - 180.2) \times 100 = 115\)

Let us consider the viscosity of oil increased to 20 deg C is 100 cs
Hence VI at 20 degC = \((369.4 - 100) / (369.4 - 180.2) \times 100 = 142\)

This implies VI decreases with increase in temperature and increases with decrease in temperature

8. **Is the viscosity of low viscosity index oils less sensitive to temperature than high VI oils? Discuss**

Note that the viscosity index is an inverse measure of the decline in oil viscosity with temperature. High values indicate that the oil shows less relative decline in viscosity with temperature.

In general to determine the viscosity index at a required temperature, viscosity is measured at the required temperature and at 100 deg C and VI is calculated from the following formula:

\[
VI = \frac{(L - \text{viscosity at required temp})}{(L - H)} \times 100
\]

\(L\) and \(H\) are values of equivalent viscosity corresponding to the viscosity of the oil at 100 deg C

Recalculating viscosity from the above formula

\[
\text{Viscosity at required temp} = L - VI \times (L - H)/100
\]

Since we are subtracting from a constant as VI is increased viscosity at required temp will be less
And if VI is less viscosity at required temperature will be more.

9. **How is viscosity index defined and can it be accurately used to evaluate modern oils**

Definition given in question 1.
Viscosity index requires tables which gives \(L\) and \(H\) values. If these data is already evaluated modern oils can also be evaluated. Initially we need to develop the data.

10. **What is the disadvantage of viscosity index? Explain**

- Viscosity index requires \(L\) and \(H\) values in it calculations. Unless \(L\) and \(H\) are available we cannot evaluate the VI.
- Viscosity of the oil is also dependent on pressure, shear rate. VI talks only changes with respect to temperature. So it does not give information about the combined effect of temperature and pressure.
- If additives are added how they are affecting the \(L\) and \(H\) values is not known.