11/01/2017

Lecture 3

Properties of Fluids

There are thermodynamic properties of fluids like:

- Pressure, p (N/m^2) or [ML^{-1}T^{-2}],
- Density, ρ (kg/m^3) or [ML^{-3}],
- Specific weight, $\gamma = \rho g$ (N/m^3) or [ML^{-2}T^{-2}],
- Viscosity, μ (Ns/m^2) or [ML^{-1}T^{-1}],
- Surface tension, σ
- Vapour pressure, etc.

  We will briefly visit some of them for the benefit of the class.

Viscosity

- It is an important property while treating fluids as a continuum.
- Viscosity is the quantitative measure of fluid's resistance to flow.
- To explain viscosity, consider a fluid element (approximated into a two-dimensional vertical plane) as shown:

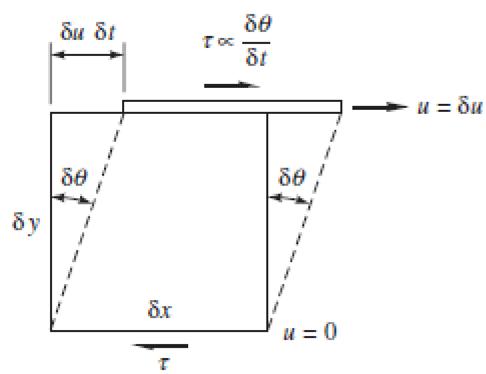

Fig. 1: Shear stress causing continuous deformation in a fluid
(Image Source: Fluid Mechanics by F.M. White)

- This element is subjected to a continuous shear stress of constant value, τ.
- As it is two-dimensional plane, the shear stress will be acting as shown in Fig. 1.
- Due to shear, the element will deform.

- After a particular interval δt, the shape of the element will be deformed as shown in Fig. 1.
- The element will be strained by an angle δθ. This shear strain angle will continuously grow with time as long as the stress τ is maintained.

- Due to shear stress, τ, the upper portion of the element will be moving at a velocity δu larger than the lower portion.
- Common fluids like water, oil, air, etc. behave such that the shear strain rate governs the shear stress of shear stress are proportional to strain rate.

  i.e. $\tau = \frac{\delta\theta}{\delta t}$

- From the above figure, it is obvious that:

  $\tan(\delta\theta) = \frac{\delta u \delta t}{\delta y}$

  For small value of δθ, the above relation becomes $\delta\theta = \frac{\delta u \delta t}{\delta y}$.

  In the limit of infinitesimal changes, this becomes a relation between shear strain rate and velocity gradient:

  $$\frac{d\theta}{dt} = \frac{du}{dy}$$

  As we know, $\tau \propto \frac{d\theta}{dt} \Rightarrow \tau \propto \frac{du}{dy}$

  Or,

  $$\tau = \mu\frac{d\theta}{dt} = \mu\frac{du}{dy}$$

❖ Please note that, here shear stress τ is linearly behaving with respect to gradient of the velocity. At the wall, due to No-slip, u=0. No-slip is characteristic of viscous flows.

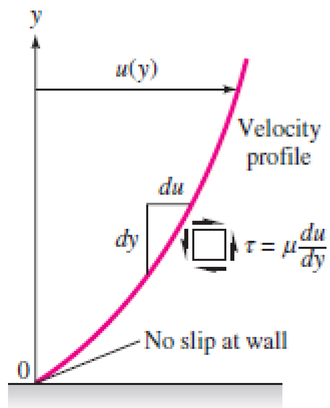

Fig. 2: Newtonian shear distribution in a shear layer near the wall, the no-slip condition ensures the velocity at the wall being zero
(Image Source: Fluid Mechanics by F.M. White)

- ❖ All liquids that follow linear relation of $\tau = \mu \frac{du}{dy}$ are called Newtonian fluids.
- ❖ Non-Newtonian fluids are those that do not obey linear law of viscosity. One can plot shear strain rate versus shear stress.

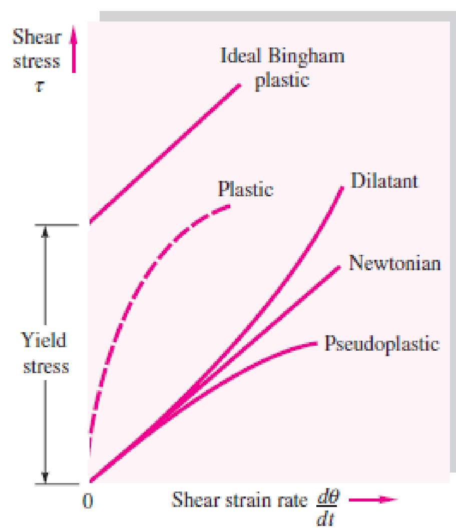

Fig. 3: Rheological behaviour of Newtonian and several non-Newtonian fluids. Note that the ideal fluids show zero viscosity
(Image Source: Fluid Mechanics by F.M. White)

Dilatants are shear thickening liquids. They show increase in resistance with strain rate. (e.g. Quick sand).
Pseudo Plastic are shear thinning liquids, which has less resistance at higher strain rates. (e.g. Blood, Plasma, Paint, Colloidal, Suspension).

Bingham Plastics are fluids that require some finite yield stress before it starts deforming (or flowing). (e.g. Mayonnaise, toothpaste, etc.).

Example: Compute the shear stress in fluid (SAE 30 oil) at 20^0C, for a case where a lower plate is fixed and upper plate is moving steadily at velocity V= 3.5 m/s and fluid fills in between space. The separation between the plates is h=2.5cm.

Ans:

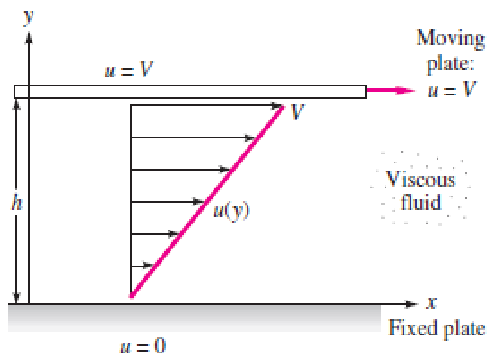

Fig. 4: Viscous flow induced by the relative motion between two parallel plates

(Image Source: Fluid Mechanics by Frank White)

SAE30 oil is Newtonian and μ_{SAE30}=0.29 kg/m-s

The problem is:

- Assuming plates are large, there will be velocity distribution in the liquid, say u(y). The velocity components v = w = 0 because the plates are large and is being moved only in one direction.
- Assume zero acceleration in flow direction.
- Also the pressure variation is considered negligible in flow direction (so that the velocity due to the pressure gradient is not considered in this case).

  If these assumptions hold, then shear stress throughout the fluid will be constant.

  i.e. $\tau = \mu \frac{du}{dy}$

$$\frac{du}{dy} = \frac{\tau}{\mu} = cons\tan t$$

Solving, u = a + by (Linear velocity)

Given:

$$u = \begin{cases} 0 = a + b(0) \, at \, y = 0 \\ V = a + b(h) \, at \, y = h \end{cases}$$

Hence, u = V $\frac{y}{h}$

⇨ $\frac{du}{dy} = \frac{V}{h}$

⇨ $\tau = \mu \frac{V}{h}$

⇨ $\tau = 0.29 * \frac{3.5}{0.025} = 40.6 N / m^2$

⇨ τ = 40.6 N/m^2

Vapour Pressure

- ❖ It is the pressure at which a liquid boils and is in equilibrium with its own vapour.
- ❖ The vapour pressure of water with respect to temperature is given in Fig. 5.

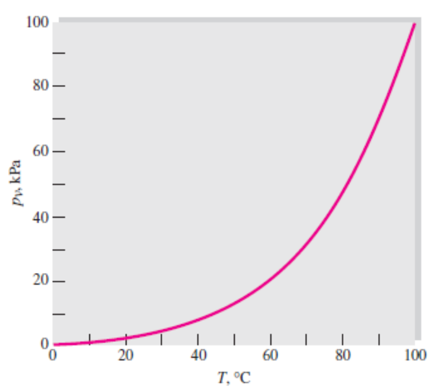

Fig. 5: Vapour pressure of water with respect to temperature

(Source: Fluid Mechanics by Frank White)

- ❖ If the liquid pressure is greater than the vapour pressure, exchange of matter occurs through evaporation between liquid and vapour.
- ❖ If the liquid pressure is less than the vapour pressure, vapour bubbles form in the liquid.
  - If the liquid pressure falls below vapour pressure due to flow phenomenon, the bubbles are formed and the process is called ***Cavitation***.
  - For example, if water is accelerated from rest to approximately 15 m/s, the pressure of it drops by nearly 1 atm.

(Note 1 atm = 1.01325 x 10^5 N/m^2 = 101.325 kPa)

- The fluid induced reduction in ambient pressure can be described using Cavitation Number.

$$C_a = \frac{p_a - p_v}{\frac{1}{2}\rho V^2}$$

Where, p_a = Ambient pressure,

p_v= Vapour pressure,

V = Characteristic flow velocity and

ρ = Flow velocity.