Viscosity

1.Introduction

When a steady shearing stress is applied to a solid, internal forces opposes the shear and establish equilibrium after a certain deformation of the solid. In contrast in case of an ideal fluid, a steady shearing stress will cause continuous displacement of the fluid as the fluid can not offer any resistance to shear. A substance in equilibrium, which can not support shearing stress, however small, is called a fluid. Due to this property a fluid attains the property to flow. In real fluid (viscous fluid) opposing force is always associated with shearing forces, which tends to destroy the relative motion and remains operative as long as the motion continuous. Viscosity in fluid flow is similar to friction in the motion of solid substances. When we slide one solid body over another we have to apply continuously an external force to overcome the frictional forces in order to keep the body in motion at constant velocity. Similarly, if the space between the two parallel plates is filled up with a fluid and the upper plate is to be kept in constant motion with respect to the lower plate, remaining at rest, a constant force is to be applied on the upper plate. The applied force opposes the effect of viscous drag of the fluid on the upper plate. The viscous drag acts not only between the upper plate and the fluid, but also among the parallel fluid layer. Viscous drag is the force of internal friction acting between adjacent layers of a fluid having stream line flow and it acts in the direction opposite to the flow.

2. Stream Line Flow

If a fluid flows in a manner that its velocity at any point always remains the same in magnitude and direction, the flow is called steady, stationary or streamline flow.

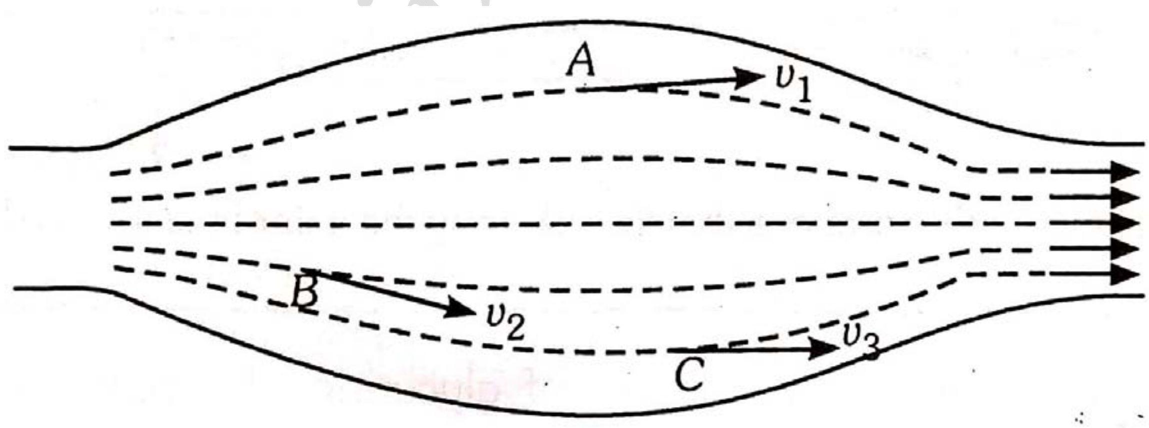

Fig1: Streamline Flow

Let us consider the flow of a fluid through a pipe as shown in the (fig1). Let the particles at the points A, B and C have velocities v_1, v_2, v_3 respectively at any instant. As time goes on such particles leave their positions at A, B and C and move forward and new particles come to the points A, B and C. if the new particles what so ever attain the velocities v_1, v_2, v_3 as soon as they come to these points respectively, the flow is called stream line flow. The path followed by a particle under this condition is called a streamline. In the fig each broken line represents a streamline. No two streamline lines will intersect since in that case particles at the point of intersection would have to move in two directions at the same time which is impossible. When the stream lines crowd together velocity of flow increases and when they remain apart velocity of flow decrease.

When streamline flow of a fluid occurs through a capillary tube of uniform cross-section, the flowing fluid can be considered as the collective flow of thin liquid concentric cylinders having radii varying from zero to the radius of the capillary. Similarly when a fluid flows steadily over a surface, the flowing fluid can be considered as the flow of thin liquid layers parallel to the surface. Such a flow is then called laminar flow. Laminar flow occurs only in limited causes when velocity is low in narrow vessels.

3. Turbulent Flow

Very often the flow becomes unsteady or turbulent when the viscosity is higher than a critical value. In turbulent flow the velocity of the particles at any given point varies with time both in direction and magnitude in an irregular way. The paths of the particle change continuously and portion of the liquid gains rotational motion forming eddies, vortices down the stream.

Fig 2: (a) Streamline flow causes no vortex behind the cylinder.
(b) Vortex is formed behind the cylinder when water flows fast.

4. Viscosity

When a liquid flows slowly and steadily over a horizontal surface, i.e., the flow is streamline, the entire liquid can be considered as the collection of infinite number of parallel liquid layers gliding over one another with different velocities. The layer in contact with the solid surface due to cohesion remains stationary. The next upper layer moves slowly over the first, the third layer moves over the second layer with a greater velocity than the second layer and so on. (Fig 3).

The speed of each layer increases as its distance from the stationary flat surface increases. The layers due to cohesion among them exert tangential force on one another. The faster moving layer tends to increase the velocity of the adjacent lower layer of lower velocity and similarly the slower moving layer tends to lower the velocity of the adjacent upper layer moving with higher velocity. The layers thus tend to destroy their relative motion and if no tangential force is applied from outside in the direction of flow to combat this tendency of destroying relative motion the flow of the liquid ceases as if a dragging force acts tangentially on the layers in the backward direction and make them stop. This intrinsic property of liquid by virtue of which it opposes the relative motion among its different layers is called viscosity. Viscous force remains operative so long a liquid flows steadily and as soon as it comes to rest the force becomes inoperative. Viscous force arises due to cohesion and is also called force of internal friction. It differs from the friction acting between two solid bodies in the manner that it depends upon

(i) The surface area of liquid layer,
(ii) Its velocity with respect to the stationary solid surface and
(iii) Its distance from the stationary surface

The tangential force, applied to the liquid surface when just balances the viscous drag, the liquid flows with a constant velocity, called terminal velocity.

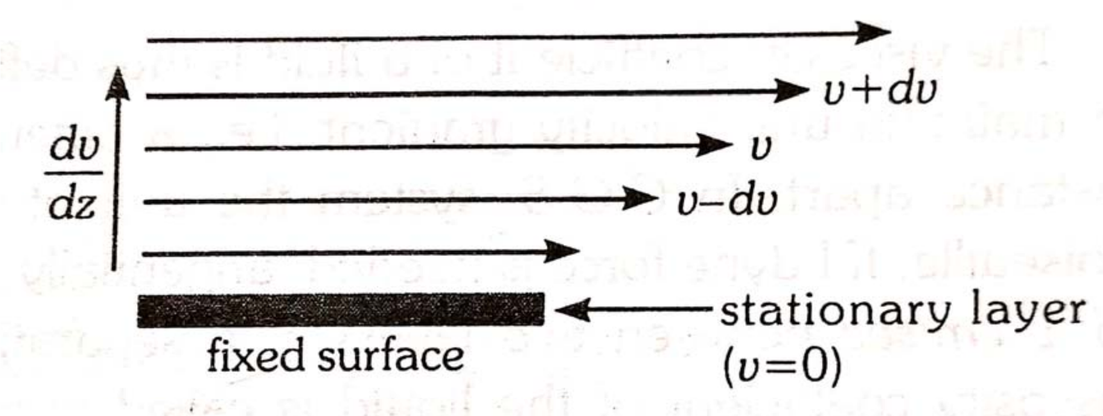

Fig 3 Laminar flow of a liquid over a flat solid surface. Positive velocity gradient acts normally away from the solid surface.

5. Viscosity Coefficient (η)

In steady flow of a liquid over a horizontal surface, velocity of the layer in contact with the solid surface is zero and the velocity of the layer increases as the distance of the layer from the solid surface increases, i.e. a velocity gradient acts normally away from the solid surface and it is positive. (Fig. 3)

During such a laminar flow the viscous drag, i.e., the tangential force acting on each layer in the direction opposite to flow, is proportional to

(i) The area of the layer and (ii) the velocity gradient.

This is Newton's law for viscous flow in the streamline motion.

So, Viscous drag, $F \propto A$ and $F \propto dv/dz$

i.e., $F = -\eta A\,(dv/dz)$ ………………………….. (1)

where, the proportionality constant η is called viscosity coefficient. The negative sign indicated that viscous force acts in the direction opposite to the direction of flow. In order to make the flow steady, tangential force is to be applied to the surface so that driving force + dragging force=0. Therefore, when the liquid flows steady with terminal velocity,

Driving force $= \eta . A . (dv/dz)$ ………………… (2)

So when A =1, dv/dz=1, driving force=η

The viscosity coefficient of a fluid is thus defined as the tangential force needed per-unit area to maintain unit velocity gradient, i.e., a difference of unit velocity between two layer at unit distance apart. In C.G.S system the unit of viscosity coefficient is **Poise**, After the name of Poiseuille. If 1 dune force is needed tangentially per sq.cm area to maintain a velocity difference of 1cm/sec between two layers at a separation of 1 cm when the liquid flows steadily, the viscosity coefficient of the liquid is called one poise.

Dimension of η:

$$\eta = \frac{F}{A\frac{dv}{dz}} = \frac{MLT^{-2}}{L^2 \frac{LT^{-1}}{L}} = ML^{-1}T^{-1}$$