Fluid flow in food processing (PART-1)

In any commercial food processing plant, the movement of liquid foods from one location to another becomes an essential operation.

Fluids are substances that flow without disintegration when pressure is applied. This definition of a fluid includes gases, liquids, and certain solids. Number of foods are in fluid state. In addition, gases such as compressed air and steam are also used in food processing and they exhibit resistance to flow just like liquids.

This module is divided into following sub-sections.

(1) Properties of Fluids

A fluid begins to move when a force acts upon it. At any location and time within a liquid transport system, several types of forces may be acting on a fluid, such as pressure, gravity, friction, thermal effects, electrical charges, etc. Both the magnitude and direction of the force acting on a fluid are important.

When force acting on a surface is perpendicular to it, the stress is called normal stress. More commonly, normal stress is referred to as pressure. When the force acts parallel to the surface, the stress is called shear stress, τ . When shear stress is applied to a fluid, the fluid cannot support the shear stress; instead the fluid deforms, or simply stated, it flows (Figure 1).

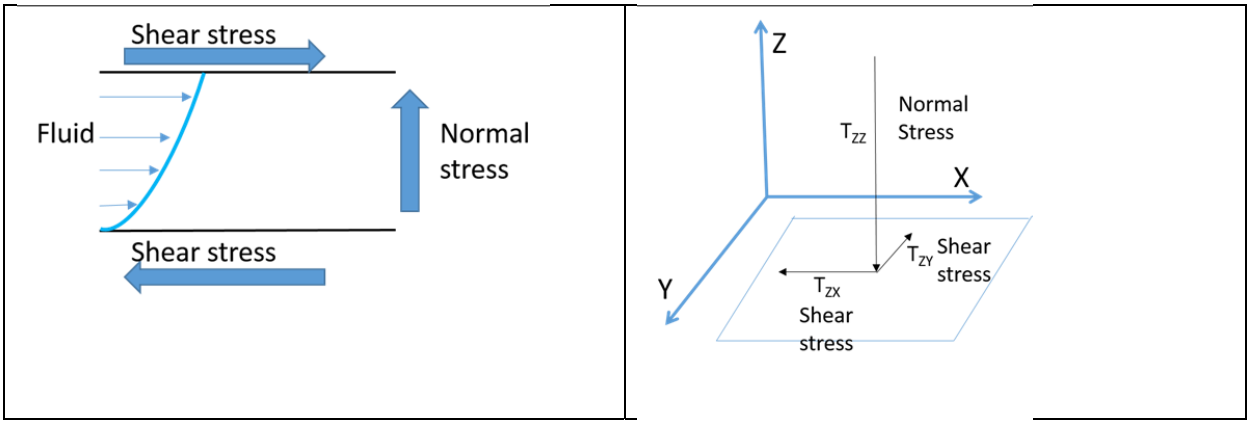

Figure 1: Shows shear and normal stress acting on (a) fluid flow (b) physical entity

When normal stress or pressure is applied on a liquid, there is no observed appreciable effect. Thus, liquids are called incompressible fluids, whereas gases are compressible fluids, since increased pressure results in considerable reduction in volume occupied by a gas.

(1.1) Density

The density of a liquid is defined as its mass per unit volume and is expressed as kg/m^3 in the SI unit system. In a physical sense, the magnitude of the density is the mass of a quantity of a given liquid occupying a defined unit volume.

Density of liquids are most often measured by a hand hydrometer. This instrument measures specific gravity, which is the ratio of the density of the given liquid to the density of water at the same temperature. See figure below

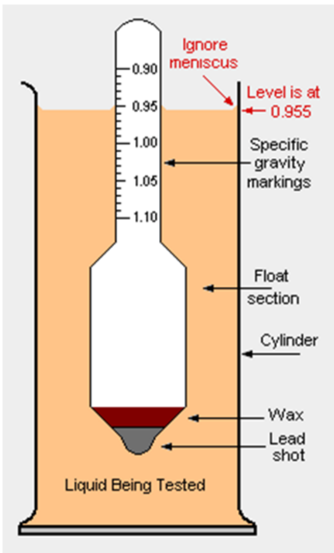

Figure 2: Hydrometer

(1.2) Concept of Viscosity

Viscosity is a measure of resistance to flow of a fluid. Although molecules of a fluid are in constant random motion, the net velocity in a particular direction is zero unless some force is applied to cause the fluid to flow. The magnitude of the force needed to induce flow at a certain velocity is related to the viscosity of a fluid. Flow occurs when fluid molecules slip past one another in a particular direction on any given plane. Thus, there must be a difference in velocity, *a velocity gradient*, between adjacent molecules.

Conceptually we can visualize that inside a fluid in motion one imaginary layer of fluid is sliding over another. The viscous forces act tangentially on the area between these imaginary layers, and they tend to oppose the flow. For instance if you spill honey—a highly viscous food—it moves much more slowly than milk, which has a substantially lower viscosity. All fluids exhibit some type of viscous behavior distinguished by a flow property called viscosity

This resistance of a material to flow or deformation is known as stress. *Shear stress* (τ) is the term given to the stress induced when molecules slip past one another along a defined plane. The velocity gradient $\left(-\frac{dV}{dr}\right)$ is a measure of how rapidly one molecule is slipping past another, therefore, it is also referred to as the *rate of shear*.

A plot of shear stress against shear rate for various fluids is shown in Fig

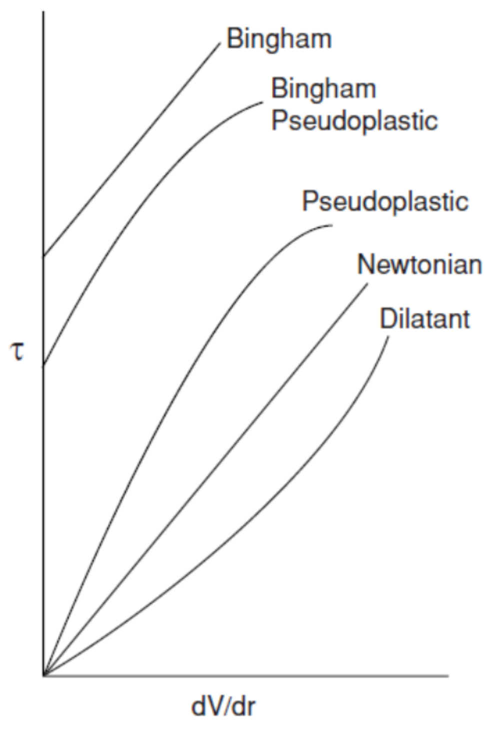

Figure 3: A plot showing the relationship between shear stress and shear rate for different types of fluids

Fluids that exhibit a linear increase in the shear stress with the rate of shear are called *Newtonian fluids*. The proportionality constant (μ) is called the *viscosity*

$$\tau = \mu\left(-\frac{dV}{dr}\right) \qquad \text{Eq. (1)}$$

Fluids with characteristics deviating from Eq. (1) are called *non-Newtonian* fluids. These fluids exhibit either shear thinning or shear thickening behavior, and some exhibit a yield stress (i.e., a threshold stress that must be overcome before the fluid starts to flow).

The two most commonly used equations for characterizing non-Newtonian fluids are the power law model (Eq. 2) and the Herschel-Bulkley model for fluids (Eq. 3):

$$\tau = K(\gamma)^n \qquad \text{Eq. (2)}$$

$$\tau = \tau_o + K(\gamma)^n \qquad \text{Eq. (3)}$$

where τ is the shear stress, γ the shear rate, τ_o the yield stress, K the consistency index, and n the flow index. If $\tau < \tau_o$ the Herschel-Bulkley fluid behaves as a solid, otherwise it behaves as a fluid. For $n < 1$ the fluid is shear-thinning, whereas for $n > 1$ the fluid is shear-thickening. If $n = 1$ and , $\tau_o = 0$ this model reduces to the Newtonian fluid.

Eq. (2) can fit the shear stress versus shear rate relationships of a wide variety of foods.

Food stuffs such as Fruit/vegetable purees and concentrates, sauces, salad dressings, mayonnaise, jams and marmalades, icecream, soups, cake mixes and cake toppings, egg white, bread mixes, snacks all fall under non-newtonian fluids

Table 1: Power Equation Parameters for Steady Viscosities of Some Foods

Food	Flow Behavior Index, n	Consistency Index K $Pa.S^n$
Butter, stick, unsalted	0.074	333
Cream Cheese, Whipped	0.061	776
Ketchup, tomato, Heinz	0.107	79.4
Peanut butter, creamy	0.168	316

Bistany and Kokini (1983). Reprinted from J. Rheology 27, page 608.

(2) Viscometry

Instruments used for measuring flow properties of fluids are called viscometers. Viscometers require a mechanism for inducing flow that should be measurable, a mechanism for measuring the applied force, and the geometry of the system in which flow is occurring must be simple in design such that the force and the flow can be translated easily into a shear stress and shear rate.

Viscometers based on fluid flow through a cylinder are called capillary or tube viscometers, depending on the inside diameter. The principle of operation is based on the Poiseuille equation (derived from Eq. (1)), if the fluid is Newtonian. The Rabinowitsch- Mooney equation (derived from Eq. (2)) applies when the fluid is non-Newtonian. Velocity profile for a liquid flowing under fully developed flow conditions and the velocity profile based on power law are derived in FAQ section (e-content) which is not part of the video content. This section has equations 4 to 15.

(2.1) Glass Capillary Viscometers

The simplest viscometer operate on gravity induced flow, and are commercially available in glass. Fig. 4 shows a Cannon-Fenske type viscometer. These viscometers are available with varying size of the capillary.

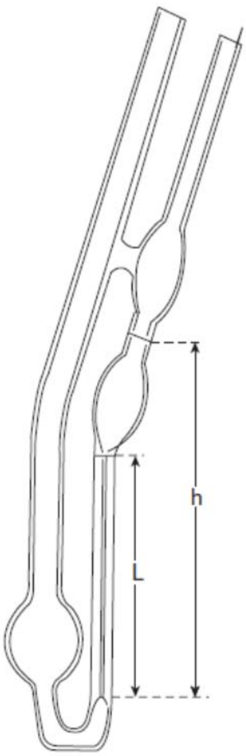

Fig. 4: Diagram of a glass capillary viscometer

The size of capillary is chosen to minimize the time of efflux for viscous fluids. The Poiseuille equation (Eq. 9, see FAQs) is used to determine the viscosity in these viscometers. The pressure drop needed to induce flow is

$$\Delta P = \rho g h$$

Where _ is the density of the fluid and h is the height available for free fall in the viscometer (Fig. 2).
The viscosity is then calculated as using the above expression for ΔP in Eq. (13) as follows:

$$\frac{\mu}{\rho} = \frac{ghR^2}{8L\bar{u}} \qquad \text{Eq. (16)}$$

The ratio $\frac{\mu}{\rho}$ is the *kinematic viscosity*

showing the components and parameters used in fitting viscometer data to the Poiseuille equation.	

The viscosity is obtained from the time of efflux of the fluid through the viscometer. To operate the viscometer, fluid is pipetted into the large leg of the viscometer until the lowermost bulb is about half full. Fluid is then drawn into the small leg to about half of the uppermost bulb. When the suction on the small leg is released, fluid will flow and timing is started when the fluid meniscus passes through the first mark. When the fluid meniscus passes the second mark, timing is stopped and the efflux time is recorded. The lower portion of the small leg of the viscometer is a capillary of radius ***R*** and length ***L***. If t_e is the time of efflux, the average velocity $\bar{u}$ will be L/t_e. Substituting in Eq. 16

$$\frac{\mu}{\rho} = \frac{ghR^2}{8L} t_e \qquad \text{Eq. (17)}$$

For each viscometer, the length and diameter of capillary, and height available for free fall, are specific, therefore, these factors can be grouped into a constant, k_v, for a particular viscometer. The kinematic viscosity can then be expressed as:

$$\frac{\mu}{\rho} = k_v t_e \qquad \text{Eq. (18)}$$

The viscometer constant is determined from the efflux time of a fluid of known viscosity and density.

Table 1: The viscosity of some common materials at room temperature

Liquid	**Viscosity, approximate(Pa s)**
Air	10^{-5}
Water	10^{-3}
Olive oil	10^{-1}
Glycerol	10^{0}
Liquid honey	10^{1}
Golden syrup	10^{2}
Glass	10^{40}

(2.2) Forced Flow Tube or Capillary Viscometry

For very viscous fluids, gravity induced flow is not sufficient to allow measurement of viscosity. Forced flow viscometers are used for these fluids. In order to obtain varying flow rates in viscometers, some means must be provided to force a fluid through the viscometer at a constant rate. This may be obtained by using a constant pressure and measuring the flow rate that develops, or by using a constant flow rate and measuring the pressure drop over a length of test section.

The flow properties of a fluid are the constants in Eq. (1) to Eq. (3), which can be used to characterize the relationship between the shear stress and the rate of shear. These are the viscosity, if the fluid is Newtonian, the flow behavior index, the consistency index, and the yield stress. Equation (3) is most general.

Evaluation of τ_o in Equation (3), from data at low shear rates is simple, once ***n*** is established from data at high shear rates. The shear rate at the wall may be determined using Eq. (12) or Eq. (15). These equations show that the shear rate is the product of some factor which is independent of the rate of flow, and another factor which is a function of the rate of flow, i.e. the average velocity, $\bar{u}$, the volumetric rate of flow ***Q***, or even the speed of a piston $\boldsymbol{V_p}$ which delivers fluid to the tube. In equation form:

$$\gamma_w = F_1\bar{u} = F_2 Q = F_3 V_p$$

The shear stress at the wall is determined by substituting R for r in Eq. (4)

$$\tau_w = \frac{\Delta PR}{2L} \qquad \text{Eq. (19)}$$

Equation (19) shows that τ_w is a product of a factor which is independent of the rate of flow, and the pressure drop.

$$\tau_w = F_{p1}(\Delta P) = F_{p2}(\text{height of manometer}) = F_{p3}(\text{Transducer output})$$

Substitution of any of the above expressions for τ_w and γ_w into Eq. (2)

$$PF_{p1} = [F_1\bar{u}]^n \qquad \text{Eq. (20)}$$

By taking logarithm and rearranging Eq. (20)

$$\log P = n\log\bar{u} + (n\log F_1 - \log F_{p1}) \qquad \text{Eq. (21)}$$

Thus, a log-log plot of any measure of pressure against any measure of velocity can give the flow behavior index ***n*** for a slope. The shear rate can then be calculated using either Eq. (12) or Eq. (15), and the shear stress can be calculated using Eq. (19).

Taking the logarithm of Eq. (2):

$$\log\tau_w = \log K + n\log\gamma_w \qquad \text{Eq. (22)}$$

The intercept of a log-log plot of γ_w against τ_w will give ***K***.

(2.3) Rotational Viscometer

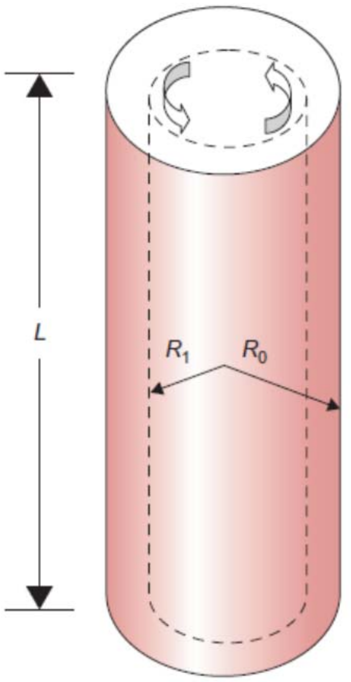

Fig. 3: A coaxial-cylinder rotational viscometer

The second type of viscometer is the rotational viscometer illustrated in Fig. 2. This illustration is more specific for a coaxial-cylinder viscometer with the liquid placed in the space between the inner and outer cylinders. The measurement involves recording of torque Ω required to turn the inner cylinder at a given number of revolutions per unit time. To calculate viscosity from the measurements, the relationships between torque Ω and shear stress τ, as well as revolutions per unit second N_r and shear rate $z_m\gamma$ must be established.

The relationship between torque Ω and shear stress τ can be shown as

$$\Omega = 2\pi r^2 L\tau \qquad \text{Eq. (23)}$$

where the length $\boldsymbol{L}$ of the cylinder and the radial location r between the inner and outer cylinder are accounted for.
The angular velocity at $\boldsymbol{r}$ is

$$u = \omega r$$

Using differential calculus,

$$\frac{du}{dr} = \omega + \frac{rd\omega}{dr}$$

We note that ω does not contribute to shear. And the shear rate γ for a rotational system becomes a function of angular velocity ω, as follows:

$$\gamma = -\frac{du}{dr} = r\left(-\frac{d\omega}{dr}\right)$$

By substitution of these relationships into Eq. (23)

$$\frac{\Omega}{2\pi r^2 L} = -\mu\left(r\frac{d\omega}{dr}\right)$$

To obtain the desired relationship for viscosity, an integration between the outer and inner cylinders must be performed

$$\int_0^{\omega_i} d\omega = -\frac{\Omega}{2\pi\mu L}\int_{R_o}^{R_i} r^{-3}dr$$

where the outer cylinder (R_o) is stationary ($\omega = 0$) and the inner cylinder (R_i) has an angular velocity $\omega = \omega_i$. The integration leads to

$$\omega_i = \frac{\Omega}{4\pi\mu L}\left(\frac{1}{R_i^2} - \frac{1}{R_o^2}\right) \qquad \text{Eq. (24)}$$

and since

$$\omega_i = 2\pi N_r$$

Note that ω is in units of radian/s and N_r is revolution/s. Then

$$\mu = \frac{\Omega}{8\pi^2 N_r L}\left(\frac{1}{R_i^2} - \frac{1}{R_o^2}\right) \qquad \text{Eq. (25)}$$

Equation (25) illustrates that liquid viscosity can be determined using a coaxial-cylinder viscometer with an inner cylinder radius R_i, length L, and outer cylinder radius R_o by measurement of torque Ω at a given N_r (revolutions per second).

A variation of the coaxial-cylinder viscometer is the single-cylinder viscometer. In this device, a single cylinder of radius R_i is immersed in a container with the test sample. Then the outer cylinder radius ***Ro*** approaches infinity, and Equation (25) becomes

$$\mu = \frac{\Omega}{8\pi^2 N_r L R_i^2} \qquad \text{Eq. (26)}$$

(3) Effect of Temperature on fluid flow

Temperature has a strong influence on the resistance to flow of a fluid. It is very important that temperatures be maintained constant when making rheological measurements. The flow behavior index, ***n***, is relatively constant with temperature, unless components of the fluid undergo chemical changes at certain temperatures. The viscosity and the consistency index on the other hand, are highly temperature dependent.

The temperature dependence of the viscosity and the consistency index can be expressed in terms of the Arrhenius equation:

$$\ln\left(\frac{\mu}{\mu_1}\right) = \frac{E_a}{R}\left(\frac{1}{T} - \frac{1}{T_1}\right) \qquad \text{Eq. (27)}$$

Where μ = the viscosity at absolute temperature T; μ_1 = viscosity at temperature T_1; E_a =the activation energy, J/gmole; R = the gas constant, 8.314 J/(gmole K); and T is the absolute temperature.

Equation (27) is useful in interpolating between values of μ at two temperatures. When data at different temperatures are available, Eq. (27) may be expressed as:

$$\ln \mu = A + \frac{B}{T}$$

where the constants B and A are slope and intercept respectively of the plot of $\ln \mu$ against 1/T. The same expressions may be used for the temperature dependence of the consistency index, K.

Conclusion

In this module, properties of fluid such as density and viscosity have been covered. Particularly, viscosity has been emphasized with details of its measurement and its effect on the fluid flow. The relationship between shear stress and shear rate have been elaborated using viscosity and the classification of the fluids into Newtonian and non-Newtonian based this relationship has been discussed. Viscosity measurement using viscometers has been covered using capillary or tube viscometers. Poiseuille and Rabinowitsch- Mooney equations were discussed which form the basis for the measurement of viscosity of the fluid. Finally the effect of temperature on the fluid flow has been detailed.