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INDEX NO.: 4015815

COURSE: FLUID TRANSPORT

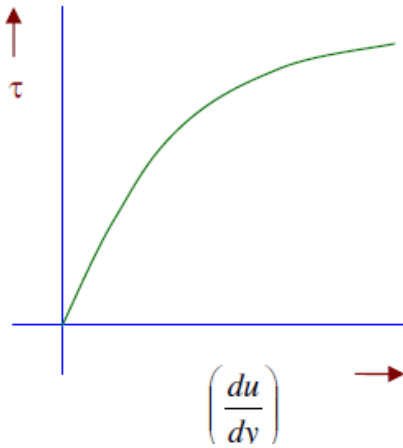
PROGRAMME: CHEMICAL ENGINEERING

ASSIGNMENT

NON NEWTONIAN FLUID

A fluid which does not obey Newton's law of viscosity is called non Newtonian fluid. For such fluids,

$$\tau = \mu \cdot \left(\frac{du}{dy} \right)^n$$



The simplest possible deviation from the Newtonian fluid behavior occurs when the simple shear data $\sigma - \dot{\gamma}$ does not pass through the origin and/ or does not result into a linear relationship between σ and $\dot{\gamma}$. Conversely, the apparent viscosity, defined as $\sigma / \dot{\gamma}$, is not constant and is a function of σ or $\dot{\gamma}$. Indeed, under appropriate circumstances, the apparent viscosity of certain materials is not only a function of flow conditions (geometry, rate of shear, etc.), but it also depends on the kinematic history of the fluid element under consideration. It is convenient, though arbitrary (and probably unscientific too), to group such materials into the following three categories:

1. Systems for which the value of $\dot{\gamma}$ at a point within the fluid is determined only by the current value of s at that point; these substances are variously known as *purely viscous*, *inelastic*, *time-independent* or *generalized Newtonian fluids (GNF)*;
2. Systems for which the relation between σ and $\dot{\gamma}$ shows further dependence on the duration of shearing and kinematic history; these are called *time-dependent fluids*, and finally,
3. Systems which exhibit a blend of viscous fluid behavior and of elastic solid-like behaviour. For instance, this class of materials shows partial elastic recovery, recoil, creep, etc. Accordingly, these are called *visco-elastic* or *elastico-viscous fluids*.

Time-Independent Fluid Behaviour

This sub-set of fluids is characterized by the fact that the current value of the rate of shear at a point in the fluid is determined only by the corresponding current value of the shear stress and vice versa. Conversely, one can say that such fluids have no memory of their past history. Thus, their steady shear behavior may be described by a relation of the form,

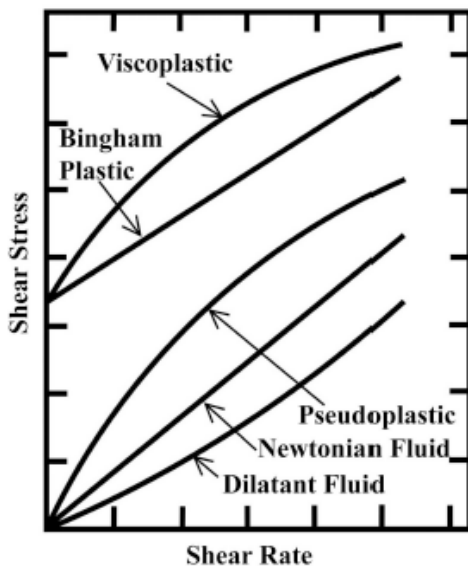
$$\dot{\gamma}_{yx} = f(\sigma_{yx}) \quad (1)$$

Or, its inverse form,

$$\sigma_{yx} = f^{-1}(\dot{\gamma}_{yx}) \quad (2)$$

Depending upon the form of equation (1) or (2), three possibilities exist:

1. Shear- thinning or pseudoplastic behavior
2. Visco-plastic behavior with or without shear-thinning behavior
3. Shear- thickening or dilatant behavior.



The figure shows qualitatively the flow curves (also called rheograms) on linear coordinates for the above noted three categories of fluid behavior; the linear relation typical of Newtonian fluids is also included

- **Shear-Thinning or Pseudoplastic Fluids**

This is perhaps the most widely encountered type of time-independent non-Newtonian fluid behavior in engineering practice. It is characterized by an apparent viscosity η (defined as $\sigma_{yx}/\dot{\gamma}_{yx}$) which gradually decreases with increasing shear rate. In polymeric systems (melts and solutions), at low shear rates, the apparent viscosity approaches a Newtonian plateau where the viscosity is independent of shear rate (zero shear viscosity, η_0).

$$\lim_{\dot{\gamma}_{yx} \rightarrow 0} \frac{\sigma_{yx}}{\dot{\gamma}_{yx}} = \eta_0$$

Furthermore, only polymer solutions also exhibit a similar plateau at very high shear rates (infinite shear viscosity, η_∞), i.e.,

$$\lim_{\dot{\gamma} \rightarrow \infty} \frac{\sigma_{yx}}{\dot{\gamma}_{yx}} = \eta_\infty$$

In most cases, the value of η_∞ is only slightly higher than the solvent viscosity η_s . The apparent viscosity of a pseudoplastic substance decreases with the increasing shear rate. Lastly, the value of shear rate marking the onset of shear-thinning is influenced by several factors such as the nature and concentration of polymer, the nature of solvent, etc for polymer solutions and particle size shape, concentration of solids in suspensions, for instance. Therefore, it is impossible to suggest valid generalizations, but many polymeric systems exhibit the zero-shear viscosity region below $\dot{\gamma} < 10^{-2} \text{ s}^{-1}$. Usually, the zero-shear viscosity region expands as the molecular weight of polymer falls, or its molecular weight distribution becomes narrower, or as the concentration of polymer in the solution is reduced. Some examples of pseudoplastic fluids are rubber latex, biological fluids like milk or blood, gelatin, fruit juice concentrates, shampoo, etc

- **Visco-plastic Fluid Behavior**

This type of non-Newtonian fluid behavior is characterized by the existence of a threshold stress (called yield stress or apparent yield stress, σ_0) which must be exceeded for the fluid to deform (shear) or flow. Conversely, such a substance will behave like an elastic solid (or flow *en masse* like a rigid body) when the externally applied stress is less than the yield stress, σ_0 . Of course, once the magnitude of the external yield stress exceeds the value of σ_0 , the fluid may exhibit Newtonian behaviour (constant value of η) or shear-thinning characteristics, i.e., $\eta(\dot{\gamma})$. It therefore stands to reason that, in the absence of surface tension effects, such a material will not level out under gravity to form an absolutely flat free surface. Quantitatively this type of behavior can be hypothesized as follows: such a substance at rest consists of three-dimensional structures of sufficient rigidity to resist any external stress less than $|\sigma_0|$ and therefore offers an enormous resistance to flow, albeit it still might deform elastically. For stress levels above $|\sigma_0|$, however, the structure breaks down and the substance behaves like a viscous material. In some cases, the build-up and breakdown of structure has been found to be reversible, i.e., the substance may regain its (initial or somewhat lower) value of the yield stress.

A fluid with a linear flow curve for $|\sigma| > |\sigma_0|$ is called a Bingham plastic fluid, and is characterized by a constant value of viscosity η_B .

On the other hand, a visco-plastic material showing shear-thinning behavior at stress levels exceeding $|\sigma_0|$ is known as a yield-pseudoplastic fluid, and their behavior is frequently approximated by the so-called Herschel-Bulkley fluid model.

Another commonly used viscosity model for visco-plastic fluids is the so-called Casson model, which has its origins in modeling the flow of blood, but it has been found a good approximation for many other substances. Typical examples of yield-stress fluids include blood, yoghurt, tomato puree, molten chocolate, tomato sauce, cosmetics, nail polishes, foams, suspensions, etc.

- ***Shear-Thickening or Dilatant Behaviour***

This class of fluids is similar to pseudoplastic systems in that they show no yield stress, but their apparent viscosity increases with the increasing shear rate and hence the name *shear-thickening*. Originally this type of behavior was observed in concentrated suspensions, and one can qualitatively explain it as follows: At rest, the voidage of the suspension is minimum and the liquid present in the sample is sufficient to fill the voids completely. At low shearing levels, the liquid lubricates the motion of each particle past another thereby minimizing solid-solid friction. Consequently, the resulting stresses are small. At high shear rates, however, the mixture expands (dilates) slightly (similar to that seen in sand dunes) so that the available liquid is no longer sufficient to fill the increased void space and to prevent direct solid-solid contacts (and friction). This leads to the development of much larger shear stresses than that seen in a pre-dilated sample at low shear rates. This mechanism causes the apparent viscosity $\eta (= \sigma / \dot{\gamma})$ to rise rapidly with the increasing rate of shear. Some examples of dilatant fluids are wet cement aggregate, concentrated starch suspension, wet beach sand, etc.

Time Dependent Behaviour

Many substances, notably in food, pharmaceutical and personal care product manufacturing sectors display flow characteristics which cannot be described by a simple mathematical expression. This is so because their apparent viscosities are not only functions of the applied shear stress (σ) or the shear rate ($\dot{\gamma}$), but also of the duration for which the fluid has been subjected to shearing as well as their previous kinematic history. For instance, the way the sample is loaded into a viscometer, by pouring or by injecting using a syringe, etc. influences the resulting values of shear stress σ or shear rate $\dot{\gamma}$. Similarly, for instance, when materials such as bentonite-in-water, coal-in-water suspensions, red mud suspensions (a waste from alumina industry), cement paste, waxy crude oil, hand lotions and creams, etc. are sheared at a constant value of $\dot{\gamma}$ following a long period of rest, their viscosities gradually decrease as the internal structures present are progressively broken down. As the number of such structural linkages capable of being broken down reduces, the rate of change of viscosity with time approaches zero. Conversely, as the structure breaks down, the rate at which linkages can re-build increases, so that eventually a state of dynamic equilibrium is reached when the rates of build-up and of break down are balanced. Similarly, there are a few systems reported in the literature in which the imposition of external shear promotes building up of internal structures and consequently their apparent viscosities increase with the duration of shearing.

Depending upon the response of a material to shear over a period of time, it is customary to sub-divide time-dependent fluid behavior into two types, namely, thixotropy and rheopexy (or negative thixotropy).

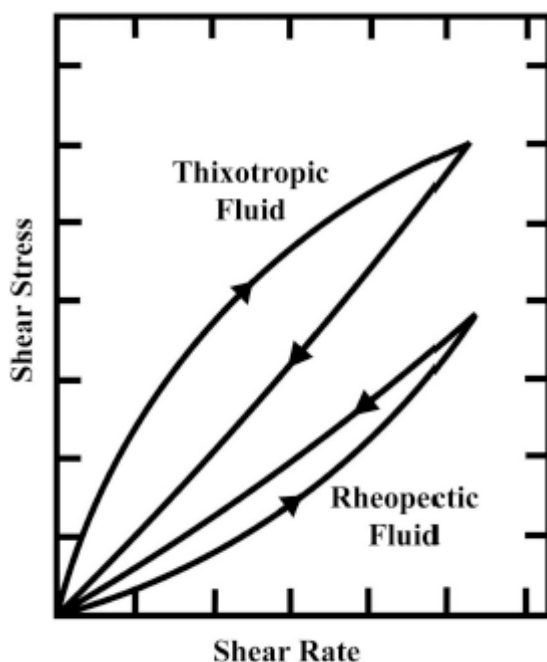
- ***Thixotropic Behaviour***

A material is classified as being thixotropic if, when it is sheared at a constant rate, its apparent viscosity $\eta = \sigma / \dot{\gamma}$ (or the value of σ because $\dot{\gamma}$ is constant) decreases with the duration of shearing. For a red mud suspension containing 59% (by wt) solids, as the value of $\dot{\gamma}$ is gradually increased, the time needed to reach the equilibrium value of σ is seen to drop dramatically.

Conversely, if the flow curve of such a fluid is measured in a single experiment in which the value of $\dot{\gamma}$ is steadily increased at a constant rate from zero to some maximum value and then decreased at the same rate, a hysteresis loop is obtained. Naturally, the height, shape and the area enclosed by the loop depend on the experimental conditions like the rate of increase/decrease of shear rate, the maximum value of shear rate, and the past kinematic history of the sample. It stands to reason that, the larger the enclosed area, more severe is the time-dependent behavior of the material under discussion. Evidently, the enclosed area would be zero for a purely viscous fluid, i.e., no hysteresis effect is expected for time-independent fluids. Some examples of thixotropic fluids are inks, many paints, cultures containing fungal mycelia, mayonnaise, etc.

- ***Rheopectic Behaviour***

The relatively few fluids which show the negative thixotropy, i.e., their apparent viscosity (or the corresponding shear stress) increases with time of shearing are also known as rheopectic fluids. In this case, the hysteresis loop is obviously inverted. As opposed to thixotropic fluids, external shear fosters the buildup of structure in this case. It is not uncommon for the same fluid to display both thixotropy as well as rheopexy under appropriate combinations of concentration and shear rate. Other examples where rheopexy has been observed include suspensions of Ammonium oleate, of Vanadium pentoxide at moderate shear rates, coal-water slurries and protein solutions.



This figure shows the qualitative shear stress – shear rate behavior for thixotropic and rheopectic materials

Visco-elastic behavior

Many materials of engineering importance show both elastic and viscous effects under appropriate circumstances. In the absence of thixotropy and rheopexy effects, the material is said to be visco-elastic. Visco-elastic fluids exhibit an elastic response to changes in shear stress. In the flow of these fluids, normal stresses in addition to the usual tangential stresses are build up. These normal stresses case for example, the fluid to climb up a shaft rotating in the fluid. When shear forces are removed from a moving visco-elastic fluid, the direction of flow may be reversed. Most visco-elastic fluids are pseudoplastic and may exhibit other rheological characteristics such as yield stress. For the steady state flow of visco-elastic fluids, the equations developed for pseudoplastic fluids apply. Examples of viscoelastic fluids are four dough, egg white and some polymer solutions like nylon, bitumen.

Reference

- *Non Newtonian Fluids: An introduction by R. P. Chhabra, Page 5 - 20*