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INTRODUCTION TO NON-NEWTONIAN FLUID

[1]Dr. Vijesh Kumar, [2]Dr.Kapil Kumar Bansal
[1]Assistant Professor, [2]Professor
[1,2]Department of Mathematics
[1]R.K.J.K. Barasia P.G. College, Surajgarh, Rajasthan
[2]Shri Rawatpura Sarkar,University,Raipur,Chhattisgarh

ABSTRACT

The best example of Newtonian fluid is water, because it continues to exemplify fluid properties no matter how fast it is stirred or mixed. Most low molecular weight substances such as organic and inorganic liquids, solutions of low molecular weight, inorganic salts, molten metals and salts and gases exhibit Newtonian flow characteristics. The consistency curve of the Newtonian fluid is a straight line passing through the origin. Other examples may be aqueous solutions of sugar or salt, silicone-oils, glycerin and emulsions/

Key words: Newtonian fluid, characteristics

INTRODUCTION

Any fluid that does not obey the Newtonian relationship between the shear stress and shear rate is called non-Newtonian. High molecular weight liquids which include molten polymers and solutions of polymers, as well as liquids in which fine particles are suspended (slurries and pastes), are usually non-Newtonian. Liquid metals also exhibit non-Newtonian flow characteristics.

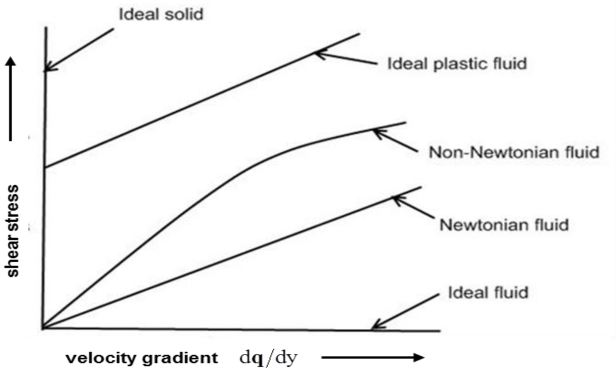

Fig. 1.1: Types of Fluids

In non-Newtonian fluids, the slope of the shear stress versus shear rate curve will not be constant as we change the shear rate. Thus, a non-Newtonian fluid is a fluid in which the viscosity changes with the applied shear force i.e. the effective viscosity does depend on that relative velocity. As a result, non-Newtonian fluids may not have a well-defined viscosity. The tendency of these particles (non-Newtonian) to line up in the plane of maximum stress has the effect of reducing the shear stress produced, thus reducing the effective or apparent viscosity. Depending on the type of non-Newtonian fluid, the viscosity can either go up or down as the fluid is sheared more. At a given point the rate of shear in a Newtonian fluid (under isothermal conditions) is proportional to the corresponding stress. A non-Newtonian fluid does not meet this requirement under all circumstances. Many of them demonstrate different properties under different flow conditions such as flow geometry, shear rate etc. and sometimes even under kinematic history of the fluids. A distinguishing feature of many non-Newtonian fluids is that they have microscopic or molecular-level structures that can be rearranged substantially in flow.

The non- Newtonian fluids are categorized into the following three groups

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

The above classification scheme is quite arbitrary, though convenient, because most real materials often display a combination of two or even all these types of features under appropriate circumstances. For instance, it is not uncommon for a polymer melt to show time-independent (shear-thinning) and visco-elastic behavior simultaneously and for a china clay suspension to exhibit a combination of time-independent (shear-thinning or shear-thickening) and time-dependent (thixotropic) features at certain concentrations and /or at appropriate shear rates. Generally, it is, however, possible to identify the dominant non-Newtonian aspect and to use it as basis for the subsequent process calculations.

TIME INDEPENDENT FLUIDS

In simple unidirectional shear, the flow behavior of this class of materials may be described by a constitutive relation of the form

$$T_{ij} = f\left(e_{ij}\right), \tag{1.1}$$

or, its inverse form

$$e_{ij} = f^{-1}\left(T_{ij}\right), \tag{1.2}$$

this equation implies that the value of the shear rate $\left(e_{ij}\right)$ at any point within the sheared fluid is determined only by the current value of shear stress $\left(T_{ij}\right)$ at that point or vice versa. Also, we can say that such fluids have no memory of their past history. These fluids may be further subdivided into three types

- shear thinning or pseudoplastic
- shear thickening or dilatant
- viscoplastic behavior with or without shear thinning behavior

SHEAR THINNING FLUIDS

For such fluids the apparent viscosity decreases with increased shear rate. Shear thinning fluids without yield stresses typically obey a power law model

$$\tau = \mu\left(\frac{d\mathbf{q}}{dy}\right)^{n} \tag{1.3}$$

over a range of shear rates. For shear thinning fluids, n<1. Shear thinning power law fluids with yield stresses are sometimes called Herschel-Bulkley fluids. Numerous other rheological model equations for shear-thinning fluids are in common use. Many shear-thinning fluids exhibit Newtonian behavior at extreme shear rates, both low and high i.e. shear stress-shear rate plots becomes straight line. Some examples of this fluid include colloids, clay, milk, gelatin, blood, liquid cement, paper pulp in water, latex paint, ice, syrup, molasses, shampoo, ketchup, fruit juice concentrates and styling gel.

SHEAR THICKENING FLUIDS:

For such fluids the apparent viscosity increases with increased shear rate. They too obey the power law except that n is always >1. Since these fluids vary exponentially, it is possible for them to be dilatant over one range of shear rates and pseudo plastic over a different range of shear rates. They are rarely encountered, but some common examples include concentrated solution of sugar in water, suspensions of rice starch or corn starch and clay slurries.

Viscoplastic Fluids:

The behavior of Viscoplastic fluids is characterized by the existence of a threshold stress (called yield stress or apparent yield stress), which must be exceeded for the fluid to deform (shear) or flow. This is a fluid that will not flow when only a small shear stress is applied. Conversely, such a substance will behave like an elastic solid (or flow like a rigid body) when the externally applied stress is less than the yield stress. Of course, once the magnitude of the external yield stress exceeds the value of yield stress, the fluid may exhibit Newtonian behavior or shear-thinning characteristics.

Bingham plastics are a special class of Viscoplastic fluids that exhibit a linear behavior of shear stress against shear rate. Examples of Viscoplastic fluids are water suspensions of clay, fly ash, toothpaste, nuclear fuel slurries, mayonnaise, tomato puree, molten chocolate, foam, yoghurt and grease.

Time Dependent Fluids : These are the fluids for which structural rearrangements occur during deformation at a rate too slow to maintain equilibrium configurations. As a result, shear stress changes with duration of shear. This means that even under a given constant shear rate, the viscosity may vary with time. Depending upon the response of a material to shear over a period of time, there are two classifications of these fluids, namely, thixotropy and rheopexy (or negative thixotropy).

Thixotropic Fluids :A fluid is said to be thixotropic if its apparent viscosity (or the corresponding shear stress) will decrease with time under a constant shear rate. However when the stress is removed, the viscosity will gradually recover with time as well. These fluids are common in the food and chemical industries. Some examples of these fluids include some drilling mud, synovial fluid, non-drip paints, tomato ketchup, most honey varieties, waxy crude oils, laponite and bentonite clay suspensions.

RheopecticFluids:

The fluids for which apparent viscosity increases with the time of shearing, exhibit rheopectic behavior. In a rheopectic fluid, the structure builds up by shear and breaks down when the material is at rest. Some examples include coal-water slurries, lubricants, whipped cream, gypsum paste and protein solutions.

Visco-Elastic Fluids:

Viscoplastic fluids are a common form of non-Newtonian fluid. They can exhibit a response that resembles that of an elastic solid under some circumstances, or the response of a viscous liquid under other circumstances. In elastic materials, the stress depends on the strain only, that is, the stress is a certain function of the strain. Thus, if we apply a certain stress on elastic material, the material undergoes some deformation and when this stress is removed the material returns to its original position. So we can say that the elastic material has memory (rather perfect memory) i.e. it is capable of recognizing its original shape. On the other hand in fluids, the stress depends upon the rate of deformation and when the stress is removed the strain rate becomes zero. But the deformation, it has accumulated persists, that is, it forgets its original position. In other words, we can say that fluid have no memory. But for visco-elastic fluids a suddenly applied and maintained state of uniform stress induces an instantaneous deformation, followed by a flow process which may or may not be limited to magnitude, as time grows i.e. both an instantaneous elastic effect and creep characteristics are exhibited. The viscosity of a viscoelastic substance gives the substance a strain rate dependent on time. When a visco-elastic fluid is in motion, a certain amount of energy is stored in materials as strain energy while some energy is lost due to viscous dissipation. In this class of fluids, unlike the case of purely viscous fluids, one can not neglect the strain, however small it may be, as it is responsible for the recovery to the original state and for the possible reverse flow that may follow the removal of the stress. During the flow the natural state of fluid changes constantly and tries to attain the instantaneous state of deformation but never succeeds completely. This lag is a measure of the elasticity or the so-called "memory" or elastic response of the fluid. So we can say that these fluids keep memory of their past deformations, and their behavior is a function of these old deformations.

A property of viscoelastic fluids is the relaxation time, which is a measure of the time required for elastic effects to decay. Viscoelastic effects may be important with sudden changes in rates of deformation, as in flows startup and stop, rapidly oscillating flows, or as a fluid passes through sudden expansions or contractions where accelerations occur. In many fully developed flows where such effects are absent, viscoelastic fluids behave as if they were purely viscous. In viscoelastic flows, normal stresses perpendicular to the direction of shear are different from those in the parallel direction (2017).

Many materials of engineering importance show both elastic and viscous effects under appropriate circumstances. Typically, fluids that exhibit this behavior are macromolecular in nature (that is, they have high molecular weight), such as polymeric fluids (melts and solutions) used to make plastic articles, food systems such as dough used to make bread and pasta, and biological fluids such as synovial fluids found in joints. The macromolecular nature of polymeric molecules along with physical interactions called entanglements lead to the elastic behavior (the fluids resemble a mass of live worms (2011). Viscoelastic fluids exhibit strange phenomena such as climbing up a rotating shaft, swelling when extruded out of a dye, etc. Some more examples of viscoelastic fluids are oil, glycerine, amorphous polymers, semi-crystalline polymers, biopolymers, metals at very high temperatures, and bitumen materials. Cracking occurs when the strain is applied quickly and outside of the elastic limit.

Viscoelastic fluids can be modeled to determine their stress or strain interactions as well as their temporal dependencies. On the basis of these models there are some viscoelastic fluids categorized as

(i) Maxwell fluid
(ii) Oldroyd-B fluid
(iii) Rivlin-Ericksen fluid
(iv) Walters' B' fluid etc.

Maxwell Fluid:

This is the fluid having both viscous and elastic properties i.e. the fluid relaxes completely to zero stress and undergoes creep indefinitely. It is assumed that the fluid is Newtonian and obeys Hooke's law for elasticity. It is named for James Clerk Maxwell who proposed the model in 1867. In a Maxwell fluid, stress, strain and their rates of change with respect to time t are governed by the equation of the form

$$T_{ij} = -\,p\,\delta_{ij} + \tau_{ij},$$

with $$\left(1+\lambda_1 \frac{\partial}{\partial t}\right)\tau_{ij} = 2\mu \frac{\partial}{\partial t}(e_{ij}),$$

where $$e_{ij} = \left(\frac{\partial q_i}{\partial x_j} + \frac{\partial q_j}{\partial x_i}\right). \tag{1.4}$$

Here λ_1 is the relaxation time for the stress with $G\left(=\frac{\mu}{\lambda_1}\right)$ as modulus of rigidity. $T_{ij}, \tau_{ij}, e_{ij}, \delta_{ij}$, q_i, x_i, p and μ denote the total stress tensor, shear stress tensor, rate of strain tensor, Kronecker delta, velocity vector, position vector, isotropic pressure and viscosity.

If the flow is steady, fluid behaves like a Newtonian fluid. If motion is stopped, the stress decays (at constant strain) as $\exp(-t/\lambda_1)$.

Oldroyd-B Fluid:

Such fluids are the combination of Maxwell and Newtonian behavior. The Oldroyd-B fluid presents one of the simplest constitutive models capable of describing the viscoelastic behavior of dilute polymeric solutions under general flow conditions. Jeffrey (1929) proposed a model to study the rheological behavior of dilute suspensions and emulsions to the idealized incompressible viscoelastic liquids at small variable shear stresses. Constitutive equation provided was

$$T_{ij}=\tau_{ij}-p\delta_{ij},$$

with $$\left(1+\lambda_1\frac{\partial}{\partial t}\right)\tau_{ij}=2\mu\left(1+\lambda_2\frac{\partial}{\partial t}\right)e_{ij},$$

where $$e_{ij}=\left(\frac{\partial q_i}{\partial x_j}+\frac{\partial q_j}{\partial x_i}\right). \tag{1.5}$$

Here $\lambda_1\left(=\frac{\mu}{G}\right)$ is the stress relaxation time and $\lambda_2\left(=\frac{\mu'}{G}\right)$ is the strain retardation time i.e. when the fluid comes to rest, any small shear decays as $\exp\left(-\frac{t}{\lambda_1}\right)$ and after becoming free from stress any small rate of strain decays as $\exp\left(-\frac{t}{\lambda_2}\right)$. Oldroyd (1953) generalized the Jeffrey's model as

$$\left(1+\lambda_1\frac{\partial}{\partial t}\right)\tau_{ij}=\mu\left(1+\lambda_2\frac{\partial}{\partial t}\right)e_{ij}. \tag{1.6}$$

Rivlin-EricksenFluid:

The constitutive equation of Rivlin-Ericksen (1955) fluid is given by

$$T_{ij}=-p\delta_{ij}+\tau_{ij},$$

with $$\tau_{ij}=\left(\mu+\mu'\frac{\partial}{\partial t}\right)e_{ij},$$

where $$e_{ij}=\left(\frac{\partial q_i}{\partial x_j}+\frac{\partial q_j}{\partial x_i}\right). \tag{1.7}$$

Here μ' is the coefficient of viscoelasticity.

Such and other polymers are used in the manufacture of parts of spacecraft, airplane, engineering equipment, seats, foams, tires, belt conveyers, ropes, cushions, plastics, adhesives, contact lens etc. Recently, polymers are also used in agriculture, communication appliances and in bio-medical appliances.

Walters' B' Fluid:

Walters (1962) proposed an elastico-viscous fluid having shear thinning and thickening characteristics. The constitutive relation for such type of fluids is

$$T_{ij} = -p\delta_{ij} + \tau_{ij},$$

with $$\tau_{ij} = \left(\mu - \mu' \frac{\partial}{\partial t}\right) e_{ij},$$

where $$e_{ij} = \left(\frac{\partial q_i}{\partial x_j} + \frac{\partial q_j}{\partial x_i}\right). \qquad (1.8)$$

Such fluids have relevance and importance in chemical technology and industry. Also, these fluids reflect the cumulative effect of many blood parameters such as plasma viscosity, red blood cell deformability, aggregation and hematocrit.

CONCLUSION

Fluid mechanics concerns itself with the investigation of motion and equilibrium of fluids. We normally recognize three states of matter: solid, liquid and gas. However, liquid and gas are both fluids: in contrast to solids they lack the ability to resist deformation. Because a fluid cannot resist the deformation force, it moves, it flows under the action of the force. Its shape will change continuously as long as the force is applied. A solid can resist a deformation force while at rest, this force may cause some displacement but the solid does not continue to move indefinitely.

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