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Rheological Behavior of Fluids

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Abstract – Rheology is the study of the deformation and flow of matter. This field aims to understand the rheological behavior of liquids by investigating the complex interactions between deformation, force, and time. Understanding the behavior of materials especially those that resemble liquid behavior is at the core of rheology. This includes the features of materials that display both liquid and solid qualities. In rheology studies, devices called rheometers are commonly used to perform various tests. These tests provide information about the flow properties and viscoelastic behaviors of liquids. In rheological analysis first section, focusing on the flow and viscosity properties of liquids, includes tests designed to measure and understand the behavior of both simple and complex fluids. On the other hand, the second section concentrates on deformation and viscoelasticity. Rheology, employed to assess the flow and deformation behaviors of liquids across a wide range of applications, plays a critical role in optimizing the design and processing of liquid products in industries such as pharmaceuticals, cosmetics, food, and manufacturing.

Keywords – Rheology, Rheological Behavior, Elastic, Viscos, Shear-Thinning

I. Introduction

Solid, liquid, and gaseous are the three aggregation states or phases that matter may form. A solid matter body has a defined form and volume that are both influenced by the forces acting on it and the temperature it is at [1]. A liquid is a body of liquid substance that lacks a defined form but has a defined volume. A container's ability to create a liquid does not always equate to filling it. A gas is a body of gaseous stuff that fills any container into which it is placed. Atoms and molecules make up matter. Interatomic forces hold the numerous atoms that make up a molecule together [2]. Intermolecular forces, which are much weaker than interatomic forces when the molecules are in the liquid or gaseous phases, are how the molecules interact. In the solid phase, the difference between molecules and atoms is no longer easily discernible. Although the molecular forces in the liquid phase are insufficient to bind the molecules to specific equilibrium positions in space, they will prevent the molecules from moving too widely apart. This explains why a liquid's volume fluctuations are generally minimal. The spaces between molecules have widened to the point that intermolecular interactions are negligible in the gaseous phase.

Liquids and gases have the characteristic of only being able to transfer a pressure normal to the solid or liquid surfaces that surround them while at rest. When a liquid or gas is moving relative to the solid or liquid surface, tangential forces on such surfaces will initially manifest. When bodies travel through air or water, these forces are felt as frictional forces on their surface [3-6].

II. RHEOLOGY

The term rheology was invented in 1920 by Professor Eugene Bingham at Lafayette College in Indiana USA. He was inspired by a colleague, Martin Reiner, professor of Chemistry, examined novel materials—especially paints—that had peculiar patterns of flow. Since the Greek word "rhein," which means flow, is spelled with the letter "rheo," the name "rheology" was originally understood to refer to the theory of matter deformation and flow [7,2]. The constitutive theory of highly viscous liquids and solids with viscoelastic and viscoplastic characteristics is also included in rheology. Newtonian fluids are fluids that obey Newton's linear law of friction, Eq. (1). An incompressible Newtonian fluid is a purely viscous fluid with a linear constitutive equation:

$$\tau = \mu\dot{\gamma} \qquad (1)$$

In the equaiton 1, shear stress τ and shear rate $\dot{\gamma}$. The coefficient μ is called the viscosity of the fluid and has the unit Ns/m^2 Pa.s, pascal-second. Alternative units for viscosity are poise (P) and centipoise (cP). Non-Newtonian fluids are defined as those that do not adhere to the linear law. These fluids often have a high viscosity, and their elastic qualities are also crucial. The theory of non-Newtonian fluids is a part of rheology. Polymer solutions, thermoplastics, drilling fluids, paints, fresh concrete, and biological fluids are examples of typical non-Newtonian fluids. Rheological parameters related with non-Newtonian viscous liquids, which include the majority of typical industrial fluids, are important to consider even if the ultimate goal is to anticipate the behavior of fluids in a variety of complex flow fields [8].

III. TYPICAL RHEOLOGICAL BEHAVIORS

A rheometer is a device that evaluates a fluid's or semi-solid's viscoelasticity as well as their viscosity. It can reveal details regarding the viscoelasticity and viscosity of the substance. Viscosity is the resistance of a substance to deformation; it depends on temperature and time as well as shear rate or stress [9]. The ability of a substance to display both viscous and elastic properties is known as viscoelasticity. For characterisation, measurements of G', G", and tan δ with regard to time, temperature, frequency, and stress/strain are crucial. Rheological analysis is performed by examining the relationship between stress and deformation.

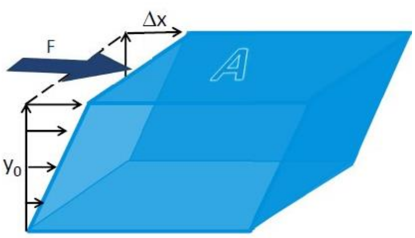

Figure 1. Stress and deformation relationship [6]

Shear stress $\tau = \frac{F}{A}$; Shear strain $\gamma = \frac{\Delta x}{y_0}$;

Shear rate= $\dot{\gamma} = \frac{1}{y_0} \cdot \frac{dx(t)}{dt}$

$$\frac{Shear\ stress}{Shear\ rate} = Viscosity \frac{stress}{strain} = Modulus$$

Stress, strain, and strain rate (shear rate) are all computed signals in a rheological measurement. Torque, together with angular displacement and angular velocity, are the raw impulses that drive the action.

Rheological behaviors may be classified into five main groups. Shear-thinning, Shear-thickening, Yield stress, Viscoelasticity, Normal stress effects, Time dependent behaviors

III. I. SHEAR-THINNING AND SHEAR-THICKENING

Pure viscous fluids in simple shear flow, where the shear stress depends only on the shear rate. If the viscosity indicated by the viscosity function decreases with increasing shear rate, a fully viscous fluid is considered shear-thinning or pseudoplastic (Fig. 2). Shear-thinning fluids represent the majority of real non-Newtonian fluids. Examples include mayonnaise, almost all polymer melts, polymer solutions, and biological fluids. The term "pseudoplastic" refers to the fact that the viscosity function of a fluid that is shear-thinning matches the viscoplastic fluid models in certain ways.
The apparent viscosity of a comparatively small group of real liquids increases as the shear rate increases (Fig. 2). These fluids are also known as dilatant fluids, or expanding fluids, or shear-thickening fluids. The expanding fluids name indicates that when these fluids are exposed to shear pressures, they frequently expand in volume. A fluid that has one effect also typically has the other, even though the two are phenomenologically very different. When the fluid behavior can be explained by a power-law model, this trend is shown as a straight line on a log-log plot (Fig. 2).

Power-law model $f(\dot{\gamma}) = K\dot{\gamma}^n$

n, power-law index and *K* the *consistency*

The power-law describes the shear thinning fluid when $n < 1$,
The power-law describes the shear thickening fluid when $n > 1$

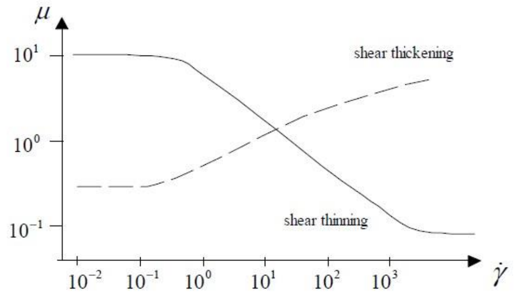

Figure 2. Sketch of a shear-thinning and shear-thickening flow [6].

III. II. YIELD STRESS

Plotting the flow curve in the $\dot{\gamma} - \tau$ plane for some fluids shows a yield stress, where the shear stress tends to a constant value when the rate is reduced to zero (Fig. 3). When working with a log-log plot, even if it is impractical to extrapolate to zero, it is customary to treat the limiting stress as a yield stress, or the stress threshold below which there is no motion.

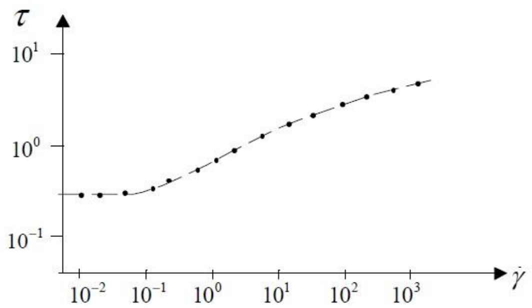

Figure 3. Diagram of a yield-stress fluid flow curve [6-9].

III. III. VISCOELASTICITY

A material undergoes deformation when it undergoes an abrupt change in its stress history, whether it be solid or fluid. There are two types of immediate deformations: elastic and plastic. When the stress is removed, the initial elastic deformation disappears, but the plastic deformation persists as a permanent deformation [10-11]. If the material is under constant stress, it may deform indefinitely in the case of a fluid or asymptotically in the case of a solid towards a finite configuration. This phenomenon is called *creep*. In the creep test performed on the rheometer, a constant stress is suddenly applied to the material and the strain change is monitored over time. When a material is deformed abruptly and maintained in that deformed state, if the material exhibits elastic behavior, the stresses could remain constant, but, if the material is fluid-like, the stress may also decrease over time, either toward an isotropic condition of stress if the material is solid-like, toward an asymptotic limit anisotropic state of stress. This mechanism is known as stress relaxation.Viscoelastic phenomena, such as creep and stress relaxation, result from the interplay between an elastic response and internal friction or viscous response in the material. A material is considered to behave viscoelastically if it shows signs of creep and stress relaxation. The material's viscoelastic qualities provide damping and energy dissipation when it is subjected to dynamic loading. Sound spreads in liquids and gasses according to an elastic response. Thus, fluids are typically both elastic and viscous, and the response is viscoelastic. But in contrast to viscous deformations, elastic deformations are small [11].

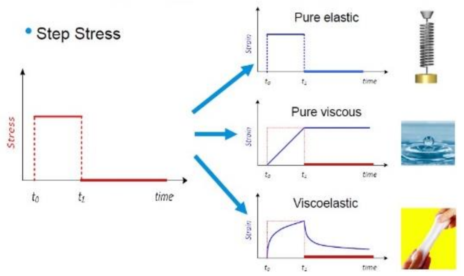

Figure 4. Sample response creep-recovery rheogram [9].

The best way to understand the concept of rheology is viscoelasticity. The complex modulus, which measures a material's entire resistance to deformation, is one of the viscoelastic characteristics. Elastic (Storage) Modulus (G'), a measurement of a material's elasticity and potential for energy storage, Viscous (loss) Modulus (G"): the material's capacity to release energy, Tan Delta: an indicator of material depletion Complex viscosity is the viscosity determined through oscillatory testing.

The easiest test is the creeping test, which involves abruptly applying a steady tension to the material and monitoring the strain change over time. Oscillatory shear experiments are employed across a range of frequencies in place of creeping testing over a range of times. The fundamental idea is to apply a strain with a sine wave shape (resp. stress) and then quantify the stress that results (resp. strain). [12].

III. IV. NORMAL STRESS EFFECTS

In this instance, normal stress effects—which are typical of polymeric fluids—are often brought on by the relaxing of the polymer coils, which had previously been expanded. Normal-stress effects can arise in a variety of circumstances and give rise to certain occurrences. Keep in mind that these effects are common for fluids that are non Newtonian, such as viscoelastic fluid. Rod-climbing or the Weissenberg effect. Examples of the die-swell effect can be provided. [13].

III. V. TIME DEPENDENT BEHAVIORS

It is very difficult to model fluids that exhibit this behavior. Their behavior is such that for a constant shear rate $\dot{\gamma}$ and at constant temperature the shear stress τ either increases or decreases monotonically with respect to time [14-16]. It takes some time for the fluids to regain their initial features once the shear rate goes to zero. There are two subgroups for the time-dependent fluids:

Thixotropic fluids have a monotonically decreasing shear stress at a constant shear rate. Rheopectic fluids have a monotonically increasing shear stress at a constant shear rate. Another name for these fluids is antithixotropic fluids [16].

IV. CONCLUSION

Rheology is primarily concerned with using continuum mechanics to appropriately combine elasticity with fluid mechanics in order to characterize the flow of materials that display a combination of elastic, viscous, and plastic behavior. Rheology finds use in the fields of physiology, human biology, geophysics, engineering, materials science, and pharmaceutics. Many industrially significant substances, like paint, foods, and cement, are made using complex flow properties thanks to the use of materials science. Furthermore, the design of metal forming processes has benefited greatly from the application of plasticity theory. Rheology, the study of viscoelastic qualities in the synthesis and use of polymeric materials, has played a major role in the creation of various items for use in the military and industrial sectors. In rheology, every group has its unique norms. While the use of oscillatory data is prevalent in polymer research, creeping tests are frequently given precedence in the rheology of particle suspension. Rheology is therefore a crucial topic for all substances and a discipline that calls for specialization in research.

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