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What is Viscosity?

OVERVIEW

Viscosity is a principal parameter when any flow measurements of fluids, such as liquids, semi-solids, gases and even solids are made. Brookfield deals with liquids and semi-solids. Viscosity measurements are made in conjunction with product quality and efficiency. Anyone involved with flow characterization, in research or development, quality control or fluid transfer, at one time or another gets involved with some type of viscosity measurement.

Many manufacturers now regard viscometers as a crucial part of their research, development, and process control programs. They know that viscosity measurements are often the quickest, most accurate and most reliable way to analyze some of the most important factors affecting product performance.

Rheological relationships help us to understand the fluids we are working with so that we can either know how they are behaving or force them to behave according to our needs.

There are many different techniques for measuring viscosity, each suitable to specific circumstances and materials. The selection of the right viscometer from the scores of instruments available to meet the need of any application is a difficult proposition. Today's instruments vary from the simple to the complex: from counting the seconds for a liquid to drain off a stick to very sophisticated automatic recording and controlling equipment. This places the instrument user in a position in which his own appreciation of the flow phenomena involved, coupled with the instrument manufacturer's "know how and experience", must be brought to bear.

Brookfield was a pioneer in the development of instrumentation for viscosity measurement and data handling and a stimulus to the development of the science. We have the requisite "know how and experience" to be your partner in the selection of proper instrumentation to control your process.

WHY MAKE RHEOLOGICAL MEASUREMENTS?

Anyone beginning the process of learning to think Rheo-Logically must first ask the question, "Why should I make a viscosity measurement?" The answer lies in the experiences of thousands of people who have made such measurements, showing that much useful behavioral and predictive information for various products can be obtained, as well as knowledge of the effects of processing, formulation changes, aging phenomena, etc.

A frequent reason for the measurement of rheological properties can be found in the area of quality control, where raw materials must be consistent from batch to batch. For this purpose, flow behavior is an indirect measure of product consistency and quality.

Another reason for making flow behavior studies is that a direct assessment of processability can be obtained. For example, a high viscosity liquid requires more power to pump than a low viscosity one. Knowing its rheological behavior, therefore, is useful when designing pumping and piping systems.

It has been suggested that rheology is the most sensitive method for material characterization because flow behavior is responsive to properties such as molecular weight and molecular weight distribution. This relationship is useful in polymer synthesis, for example, because it allows relative differences to be seen without making molecular weight measurements. Rheological measurements are also useful in following the course of a chemical reaction. Such measurements can be employed as a quality check during production or to monitor and/or control a process. Rheological measurements allow the study of chemical, mechanical, and thermal treatments, the effects of additives, or the course of a curing reaction. They are also a way to predict and control a host of product properties, end use performance and material behavior.

THINKING RHEO-LOGICALLY

To begin, consider the question, "Can some rheological parameter be employed to correlate with an aspect of the product or process?" To determine this, an instinct must be developed for the kinds of chemical and physical phenomena which affect the rheological response. For the moment, assume this information is known and several possibilities have been identified. The next step is to gather preliminary rheological data to determine what type of flow behavior is characteristic of the system under consideration. At the most basic level, this involves making measurements with whichever Brookfield Viscometer is available and drawing some conclusions based on the descriptions of flow behavior that follow.

Once the type of flow behavior has been identified, more can be understood about the way components of the system interact. The data thus obtained may then be fitted to one of the mathematical models which have been successfully used with Brookfield instruments.

Such mathematical models range from the very simple to the very complex. Some of them merely involve the plotting of data on graph paper; others require calculating the ratio of two numbers. Some are quite sophisticated and require use of programmable calculators or computers. This kind of analysis is the best way for getting the most from our data and often results in one of two constants which summarize the data and can be related to product or process performance.

Once a correlation has been developed between rheological data and product behavior, the procedure can then be reversed and rheological data may be used to predict performance and behavior.

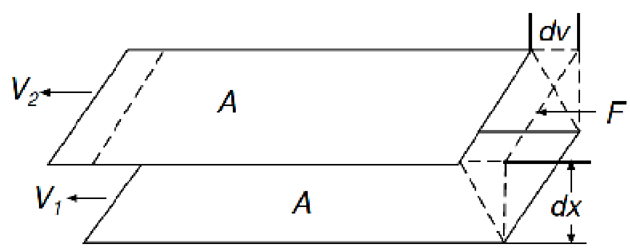
COMING TO GRIPS WITH RHEOLOGY

Rheology is defined by Webster's Dictionary as "the study of the change in form and the flow of matter, embracing elasticity, viscosity, and plasticity.
We concern ourselves in this chapter with viscosity, further defined as

the internal friction of a fluid, caused by molecular attraction, which makes it resist a tendency to flow. Your Brookfield Viscometer measures this friction, and therefore functions as a tool of rheology. The purpose of this chapter is to acquaint you with the different types of flow behavior and use of the Brookfield Viscometer as a rheological instrument to enable you to conduct a detailed analysis of virtually any fluid. This information is useful to all Viscometer users, particularly those adhering to the Theoretical and Academic schools of thought on viscosity measurement.

VISCOSITY

Viscosity is the measure of the internal friction of a fluid. This friction becomes apparent when a layer of fluid is made to move in relation to another layer. The greater the friction, the greater the amount of force required to cause this movement, which is called shear. Shearing occurs whenever the fluid is physically moved or distributed, as in pouring, spreading, spraying, mixing, etc. Highly viscous fluids, therefore, require more force to move than less viscous materials.



Isaac Newton defined viscosity by considering the model represented in the figure above. Two parallel planes of fluid of equal area A are separated by a distance dx and are moving in the same direction at different velocities V1 and V2. Newton assumed that the force required to maintain this difference in speed was proportional to the difference in speed through the liquid, or the velocity gradient. To express this, Newton wrote:

$$\frac{F}{A} = \eta \frac{dv}{dx}$$

where η is a constant for a given material and is called its viscosity.

The velocity gradient, dv/dx , is a measure of the change in speed at which the intermediate layers move with respect to each other. It describes the shearing the liquid experiences and is thus called shear rate. This will be symbolized as S in subsequent discussions. Its unit of measure is called the reciprocal second (sec-1).

The term F/A indicates the force per unit area required to produce the shearing action. It is referred to as shear stress and will be symbolized by F′. Its unit of measurement is dynes per square centimeter (dynes/cm2).

Using these simplified terms, viscosity may be defined mathematically by this formula:

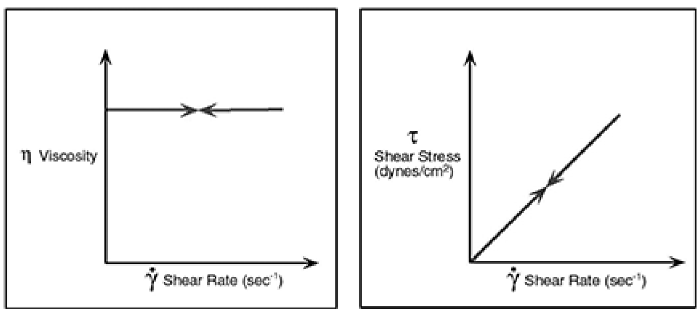
$$\eta = \text{viscosity} = \frac{\tau}{\dot{\gamma}} = \frac{\text{shear stress}}{\text{shear rate}}$$

The fundamental unit of viscosity measurement is the poise. A material requiring a shear stress of one dyne per square centimeter to produce a shear rate of one reciprocal second has a viscosity of one poise, or 100 centipoise. You will encounter viscosity measurements expressed in Pascal-seconds (Pa·s) or milli-Pascal-seconds (mPa·s); these are units of the International System and are sometimes used in preference to the Metric designations. One Pascal-second is equal to ten poise; one milli-Pascal-second is equal to one centipoise.

Newton assumed that all materials have, at a given temperature, a viscosity that is independent of the shear rate. In other words, twice the force would move the fluid twice as fast. As we shall see, Newton was only partly right.

NEWTONIAN FLUIDS

This type of flow behavior Newton assumed for all fluids is called, not surprisingly, Newtonian. It is, however, only one of several types of flow behavior you may encounter. A Newtonian fluid is represented graphically in the figure below. Graph A shows that the relationship between shear stress (F′) and shear rate (S) is a straight line. Graph B shows that the fluid's viscosity remains constant as the shear rate is varied. Typical Newtonian fluids include water and thin motor oils.



What this means in practice is that at a given temperature the viscosity of a Newtonian fluid will remain constant regardless of which Viscometer model, spindle or speed you use to measure it. Brookfield Viscosity Standards are Newtonian within the range of shear rates generated by Brookfield equipment; that's why they are usable with all our Viscometer models. Newtonians are obviously the easiest fluids to measure - just grab your Viscometer and go to it. They are not, unfortunately, as common as that much more complex group of fluids, the non-Newtonians, which will be discussed in the next section.

NON-NEWTONIAN FLUIDS

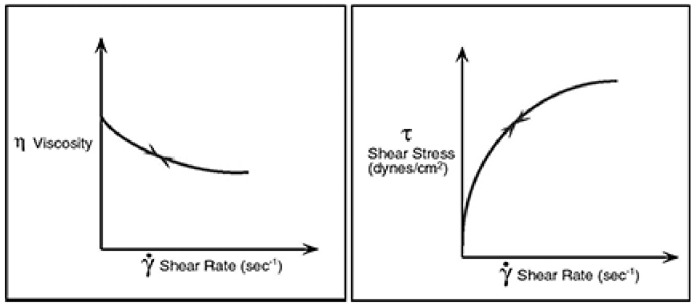
A non-Newtonian fluid is broadly defined as one for which the relationship F′/S is not a constant. In other words, when the shear rate is varied, the shear stress doesn't vary in the same proportion (or even necessarily in the same direction). The viscosity of such fluids will therefore change as the shear rate is varied. Thus, the experimental parameters of Viscometer model, spindle and speed all have an effect on the measured viscosity of a non-Newtonian fluid. This measured viscosity is called the apparent viscosity of the fluid and is accurate only when explicit experimental parameters are furnished and adhered to.

Non-Newtonian flow can be envisioned by thinking of any fluid as a mixture of molecules with different shapes and sizes. As they pass by each other, as happens during flow, their size, shape, and cohesiveness will determine how much force is required to move them. At each specific rate of shear, the alignment may be different and more or less force may be required to maintain motion.

There are several types of non-Newtonian flow behavior, characterized by the way a fluid's viscosity changes in response to variations in shear rate. The most common types of non-Newtonian fluids you may encounter include:

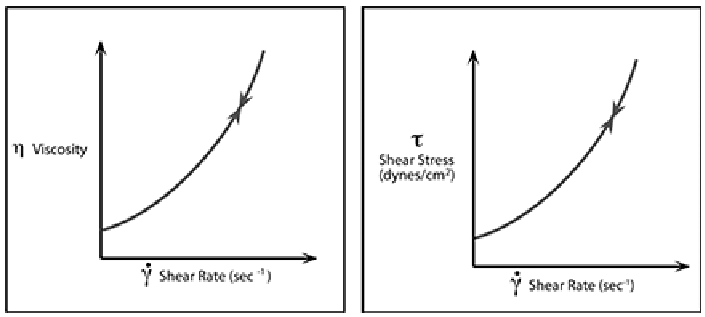
Psuedoplastic

This type of fluid will display a decreasing viscosity with an increasing shear rate, as shown in the figure below. Probably the most common of the non-Newtonian fluids, pseudo-plastics include paints, emulsions, and dispersions of many types. This type of flow behavior is sometimes called shear-thinning.



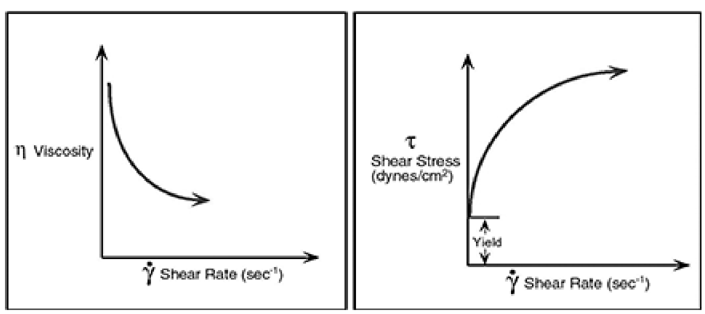
Dilatant

Increasing viscosity with an increase in shear rate characterizes the dilatant fluid; see the figure below. Although rarer than pseudoplasticity, dilatancy is frequently observed in fluids containing high levels of deflocculated solids, such as clay slurries, candy compounds, corn starch in water, and sand/water mixtures. Dilatancy is also referred to as shear-thickening flow behavior.



Plastic

This type of fluid will behave as a solid under static conditions. A certain amount of force must be applied to the fluid before any flow is induced; this force is called the yield value. Tomato catsup is a good example of this type fluid; its yield value will often make it refuse to pour from the bottle until the bottle is shaken or struck, allowing the catsup to gush freely. Once the yield value is exceeded and flow begins, plastic fluids may display Newtonian, pseudoplastic, or dilatant flow characteristics. See the figure below.



So far we have only discussed the effect of shear rate on non-Newtonian fluids. What happens when the element of time is considered? This question leads us to the examination of two more types of non-Newtonian flow: thixotropic and rheopectic.

THIXOTROPY AND RHEOPEXY

Some fluids will display a change in viscosity with time under conditions of constant shear rate. There are two categories to consider:

Thixotropy

As shown in the figure below, a thixotropic fluid undergoes a decrease in viscosity with time, while it is subjected to constant shearing.

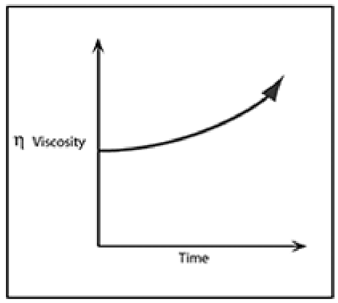
Rheopexy

This is essentially the opposite of thixotropic behavior, in that the fluid's viscosity increases with time as it is sheared at a constant rate. See the figure below.

Both thixotropy and rheopexy may occur in combination with any of the previously discussed flow behaviors, or only at certain shear rates. The time element is extremely variable; under conditions of constant shear, some fluids will reach their final viscosity value in a few seconds, while others may take up to several days.

Rheopectic fluids are rarely encountered. Thixotropy, however, is frequently observed in materials such as greases, heavy printing inks, and paints.

When subjected to varying rates of shear, a thixotropic fluid will react as illustrated in the figure below. A plot of shear stress versus shear rate was made as the shear rate was increased to a certain value, then immediately decreased to the starting point. Note that the up and down curves do not coincide. This hysteresis loop is caused by the decrease in the fluid's viscosity with increasing time of shearing. Such effects may or may not be reversible; some thixotropic fluids, if allowed to stand undisturbed for a while, will regain their initial viscosity, while others never will.



The rheological behavior of a fluid can, of course, have a profound effect on viscosity measurement technique. Later we will discuss some of these effects and ways of dealing with them.

LAMINAR AND TURBULENT FLOW

The very definition of viscosity implies the existence of what is called laminar flow: the movement of one layer of fluid past another with no transfer of matter from one to the other. Viscosity is the friction between these layers.

Depending on a number of factors, there is a certain maximum speed at which one layer of fluid can move with relation to another, beyond which an actual transfer of mass occurs. This is called turbulence. Molecules or larger particles jump from one layer to another and dissipate a substantial amount of energy in the process. The net result is that a larger energy input is required to maintain this turbulent flow than a laminar flow at the same velocity.

The increased energy input is manifested as an apparently greater shear stress than would be observed under laminar flow conditions at the same shear rate. This results in an erroneously high viscosity reading.

The point at which laminar flow evolves into turbulent flow depends on other factors besides the velocity at which the layers move. A material's viscosity and specific gravity as well as the geometry of the Viscometer spindle and sample container all influence the point at which this transition occurs.

Care should be taken to distinguish between turbulent flow conditions and dilatant flow behavior. In general, dilatant materials will show a steadily increasing viscosity with increasing shear rate; turbulent flow is characterized by a relatively sudden and substantial increase in viscosity above a certain shear rate. The material's flow behavior may be Newtonian or non-Newtonian below this point.

Due to the relatively low shear rates at which most Brookfield Viscometers operate, it is unlikely that you will encounter turbulent flow unless you are measuring viscosities lower than 15 cP with an LV series Viscometer or 85 cP with other models. The higher the viscosity of a fluid, the less likely it is to experience turbulence. If turbulence is observed while measuring low viscosity fluids, it can often be eliminated by using the UL Adapter™ accessory.

WHAT AFFECTS THE RHEOLOGICAL PROPERTY?

Viscosity data often functions as a "window" through which other characteristics of a material may be observed. Viscosity is more easily measured than some of the properties that affect it, making it a valuable tool for material characterization. Earlier in this chapter we discussed various types of rheological behavior and how to identify them. Having identified a particular rheological behavior in a material, you may wonder what this information implies about its other characteristics. This section, based on information gleaned from years of customer experience, is intended as a "tickler" to get you thinking about the mysteries your Viscometer can help you solve.

Temperature

One of the most obvious factors that can have an effect on the rheological behavior of a material is temperature. Some materials are quite sensitive to temperature, and a relatively small variation will result in a significant change in viscosity. Others are relatively insensitive. Consideration of the effect of temperature on viscosity is essential in the evaluation of materials that will be subjected to temperature variations in use or processing, such as motor oils, greases, and hot-melt adhesives.

Shear Rate

Non-Newtonian fluids tend to be the rule rather than the exception in the real world, making an appreciation of the effects of shear rate a necessity for anyone engaged in the practical application of rheological data. It would, for example, be disastrous to try to pump a dilatant fluid through a system, only to have it go solid inside the pump, bringing the whole process to an abrupt halt. While this is an extreme example, the importance of shear rate effects should not be underestimated.

When a material is to be subjected to a variety of shear rates in processing or use, it is essential to know its viscosity at the projected shear rates. If these are not known, an estimate should be made. Viscosity measurements should then be made at shear rates as close as possible to the estimated values.

It is frequently impossible to approximate projected shear rate values during measurement due to these values falling outside the shear rate range of the Viscometer. In this case, it is necessary to make measurements at several shear rates and extrapolate the data to the projected values. This is not the most accurate method for acquiring this information, but it is often the only alternative available, especially when the projected shear rates are very high. In fact, it is always advisable to make viscosity measurements at several shear rates to detect rheological behavior that may have an effect on processing or use. Where shear rate values are unknown or not important, a sample plot of viscosity versus RPM will often suffice.

Examples of materials that are subjected to, and are affected by, wide variations in shear rate during processing and use are: paints, cosmetics, liquid latex, coatings, certain food products, and blood in the human circulatory system. The following table shows typical examples of varying shear rates.

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