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AN INTRODUCTORY GUIDE TO RHEOLOGY

June, 1995 Volume VII

A basic understanding of Rheology, the science dealing with the deformation and flow of matter, is needed to appreciate why this is important to printing inks. Shear Stress, Shear Rate, and Viscosity are the building blocks leading to an understanding of rheology. Viscosity is a measure of a fluid's resistance to flow. When a fluid starts to flow under the action of a force, a shearing stress arises everywhere in that fluid that tends to oppose the motion. As one layer of the fluid moves past an adjacent layer, the fluid's molecules interact so as to transmit momentum from the faster layer to the slower layer tending to resist the relative motion. The intent of this report is to explain the fundamentals of rheology and to acquaint you with the different types of flow behavior.

RHEOLOGY

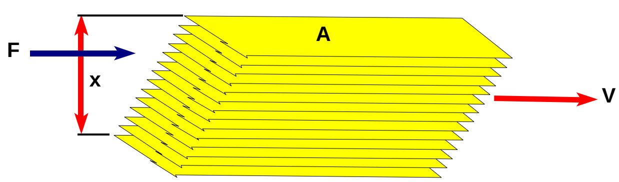
DEFINITION

- Study of Flow and Deformation of Matter

Figure 1

The distinguishing feature of a fluid, in contrast to a solid, is the ease with which the fluid may be deformed. If a shearing force, however small, is applied to a fluid, the fluid will move and continue to move as long as the force acts on it. For example, the force of gravity causes water poured from a pitcher to flow; it will continue to flow as long as the pitcher is tilted. If the pitcher is turned back up the flow ceases because the gravitational force is then exactly balanced by the pressure force of the pitcher wall.

SHEAR RATE AND STRESS



- Shearing Stress = Force/Area (Newton/Square Meters)
- Shearing Rate = Change in Velocity/Distance (1/Seconds)
- Must Control One of these and Measure the other usually with well defined conditions

Figure 2

Even though a fluid can deform easily under an applied force, the fluid's viscosity creates resistance to this force. Viscosity can be appreciated by visualizing a cube of fluid between two plates as shown in Figure 2. If a shearing force (F) is applied to the top plate (A), this plate will move at a specific velocity (V). The layer of fluid immediately below the plate will also move, reaching a velocity almost but not equal to that of the plate. In the same way, each successively lower layer of fluid will move at a velocity less than that of its immediate predecessor so that the last layer is almost motionless. The force applied to the top plate divided by the area (A) of the top plate is defined as shear stress and is typically expressed in units of Newtons per square meter. The velocity gradient or, more commonly, the shear rate is the differential change in velocity divided by the distance between the top and bottom plates and is expressed in units of reciprocal seconds. The viscosity of a fluid is derived from these two properties. Viscosity is defined as the ratio of shear stress to shear rate (see Figure 3).

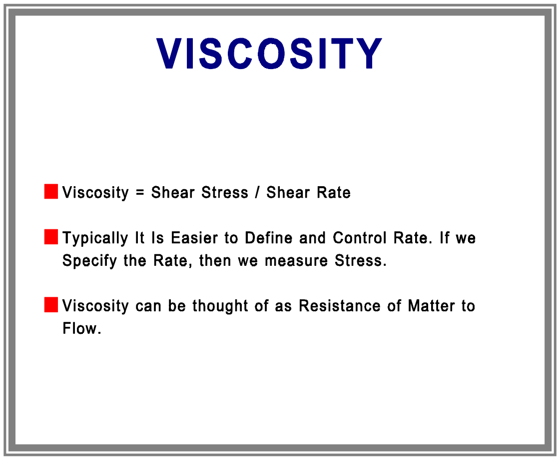


Figure 3

Sir Isaac Newton was the first to define viscosity by considering the model represented in Figure 2. Newton assumed the force required to maintain a difference in speed was proportional to the difference in speed through a liquid. This simple relationship in fluids for which the shear stress divided by the shear rate which remains equal independent of the shear rate, would be called a Newtonian fluid (See Figure 4). As we shall see, Newton was only part right.

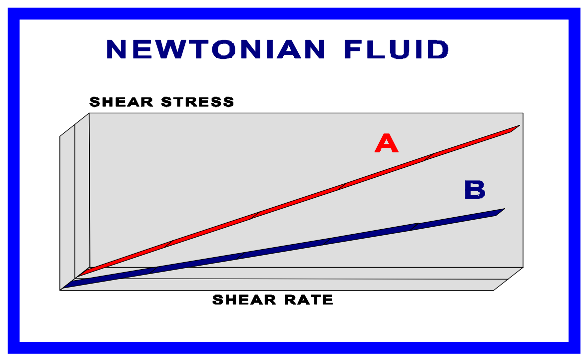


Figure 4

What this means in practice is that at a given temperature the viscosity of a Newtonian fluid will remain constant, regardless of the shear rate used to measure it (see Figure 5). Typical Newtonian fluids include water and thin motor oils. Newtonian fluids are often pure fluids, not dispersions. Newtonian fluids are the easiest fluids to measure. They are not, unfortunately, as common as the more complex fluids described as non-Newtonian.

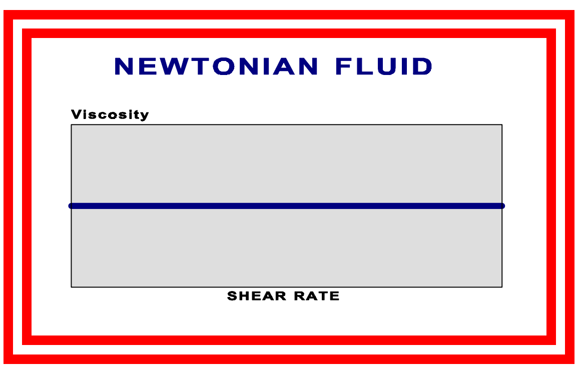


Figure 5

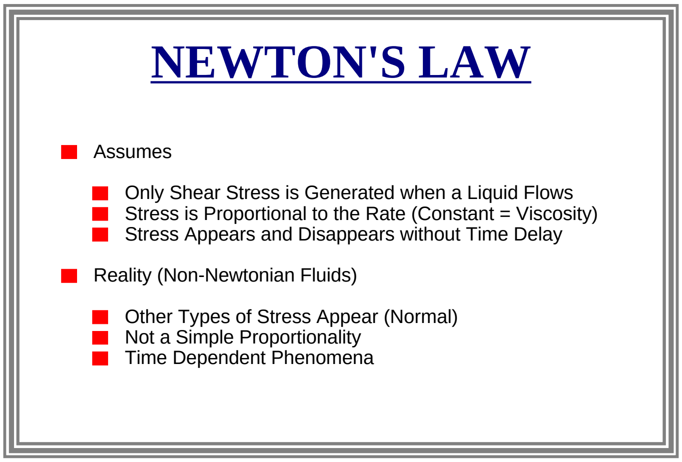


Figure 6

As we stated before, Newton was only partially right; many fluids can be described as non-Newtonian. A non-Newtonian fluid is broadly defined as one in which the relationship between the shear stress and shear rate is not a constant (see Figure 7). In other words, when the shear rate is varied, the shear stress does not 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. This measured viscosity is called the "apparent viscosity" and is accurate only when explicit experimental parameters are furnished and followed.

There are several types of non-Newtonian flow behaviors, 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:

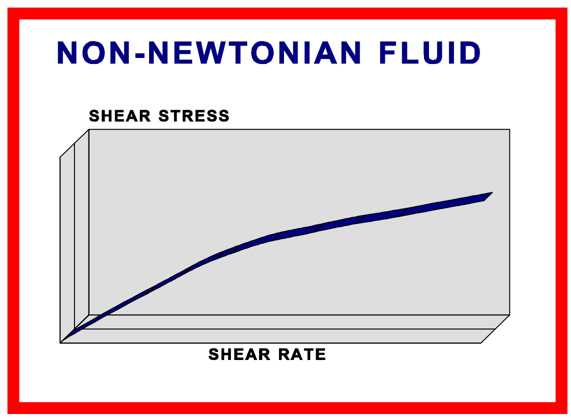


Figure 7

PSEUDO PLASTIC This type of fluid will display a decreasing viscosity with an increasing shear rate, as shown in Figure 8. Probably the most common of the non-Newtonian fluids, pseudo plastics include inks, paints, emulsions, and dispersions of many types. This type of flow behavior is sometimes called "shear-thinning."

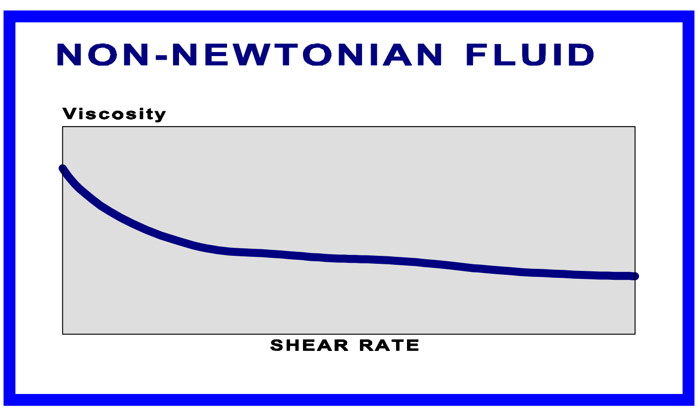


Figure 8

DILATANT Increasing viscosity with an increase in shear rate characterizes the dilatant fluid. 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. This type of property is almost never found in printing inks.

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 another type of non-Newtonian flow called "thixotropy." Some fluids will display a change in viscosity with time under conditions of constant shear rate.

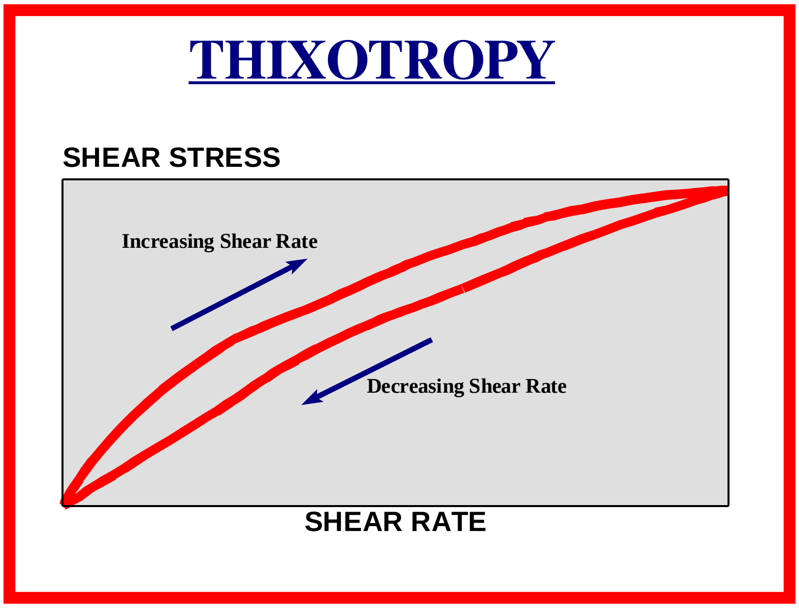


Figure 9

Thixotropy 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.

When subjected to varying rates of shear, a thixotropic fluid will react as illustrated in Figure 9. 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.

Many printing ink formulations exhibit this property, so that the proper balance between setting of the ink film and dripping of the ink can be carefully controlled.

What Affects the Rheological Properties?

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. Having identified a particular rheological behavior in a material, you may wonder what this information implies about its other characteristics.

VISCOSITY DEPENDS ON

- Shear Rate
- Temperature
- Pressure
- Time (History of Shear)
- Physical / Chemical Properties
  - For Ink - Oils, Resins, Pigment, etc.

Figure 10

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. The typical shear rates encountered in the printing ink environment are shown in Figure 11.

SHEAR RATE LIFE CYCLE

TYPICAL INK

PROCESS	SHEAR RATE	TIME
Storage	0.001 -0.00001	Days
Pumping	1 - 1000	Minutes
Roller Nip	10,000 - 10,000,000	Fraction of Second
Leveling	0.001 - .1	Seconds
Draining	0.1 - 10	Minutes

Figure 11

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. Printing inks are sensitive to temperature, so the temperature must be carefully controlled when measuring rheological properties.

Time

The time elapsed under conditions of shear obviously affects thixotropic materials, but changes in viscosity of many materials can occur over time. Aging phenomena must be considered when selecting and preparing samples for viscosity measurement.

Physical / Chemical Properties

The composition of a material is a determining factor of its viscosity. When this composition is altered, either by changing the proportions of the component substances, or by the addition of other materials, a change in viscosity is very likely. For example, the addition of a solvent to printing inks will lower the viscosity.

As one can see, Rheology is a very complex subject. In the formulation of a printing ink, many different types of viscosity measurements are made to define the proper viscosity profile. Once a formulation has been finalized, defined procedures are followed to properly measure the consistency of the batches produced. If these procedures are not followed, drastically different values for the viscosity of the same ink can be produced. There is no standardized test method for the no-heat printing industry. Each ink manufacturer follows their own test methods. Therefore, one cannot compare viscosity measurements from different sources unless the same measurement procedures have been followed.