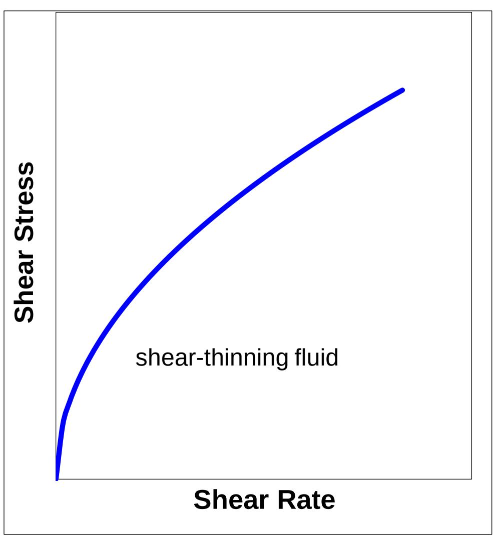
Non-Newtonian Flows

R. Shankar Subramanian
Department of Chemical and Biomolecular Engineering
Clarkson University

Fluids such as water, air, ethanol, and benzene are Newtonian. This means that a plot of shear stress versus shear rate at a given temperature is a straight line with a constant slope that is independent of the shear rate. We call this slope the viscosity of the fluid. Also, the plot passes through the origin, that is, the shear rate is zero when the shear stress is zero. All gases are Newtonian. Also, low molecular weight liquids, and solutions of low molecular weight substances in liquids are usually Newtonian. Some examples are aqueous solutions of sugar or salt.

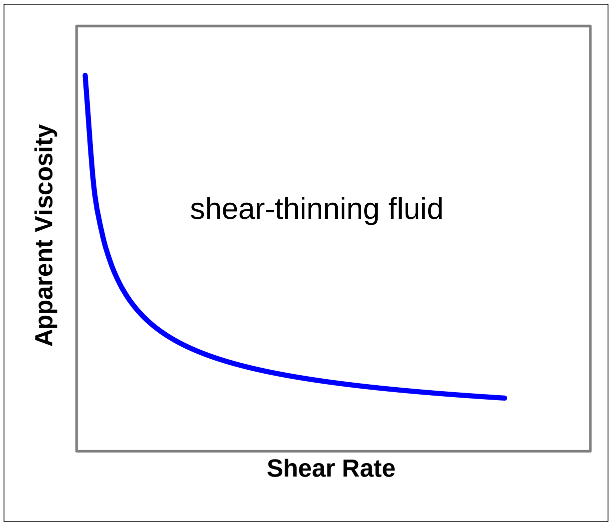
Any fluid that does not obey the Newtonian relationship between the shear stress and shear rate is called non-Newtonian. The subject of "Rheology" is devoted to the study of the behavior of such fluids. High molecular weight liquids, which include polymer melts and solutions of polymers, as well as liquids in which fine particles are suspended (slurries and pastes), are usually non-Newtonian. In this case, the slope of the shear stress versus shear rate curve will not be constant as we change the shear rate. When the viscosity decreases with increasing shear rate, we call the fluid shear-thinning. In the opposite case where the viscosity increases as the fluid is subjected to a higher shear rate, the fluid is called shear-thickening. Shear-thinning behavior is more common than shear-thickening. Shear-thinning fluids also are called pseudoplastic fluids. A typical shear stress versus shear rate plot for a shear-thinning fluid looks like this.



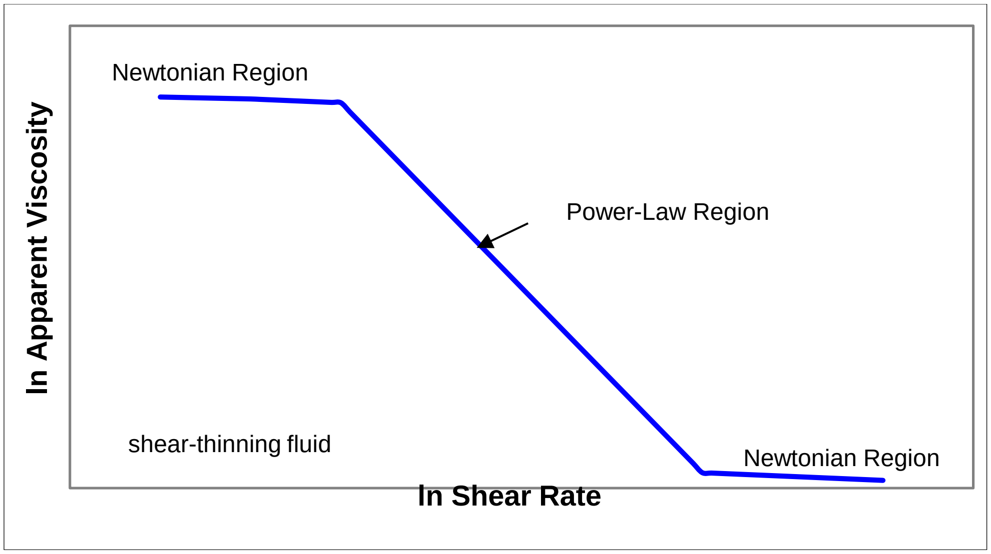
We describe the relationship between the shear stress τ and shear rate $\dot{\theta}$ as follows.

$$\tau = \eta\dot{\theta}$$

Here, η is called the "apparent viscosity" of the fluid, and is a function of the shear rate. In the above example, a plot of η as a function of the shear rate $\dot{\theta}$ looks like this.



Many shear-thinning fluids will exhibit Newtonian behavior at extreme shear rates, both low and high. For such fluids, when ln (apparent viscosity) is plotted against ln (shear rate), we see a curve like this.



The regions where the apparent viscosity is approximately constant are known as Newtonian regions. The behavior between these regions can usually be approximated by a straight line on these axes. It is known as the power-law region. In this region, we can approximate the behavior by

$$\ln\eta = a + b\ln\dot{\theta}$$

which can be rewritten as

$$\eta = K\dot{\theta}^{b}$$

where $K = \exp(a)$. Instead of b we commonly use $(n-1)$ for the exponent and write a result for the apparent viscosity as follows.

$$\eta = K\dot{\theta}^{n-1}$$

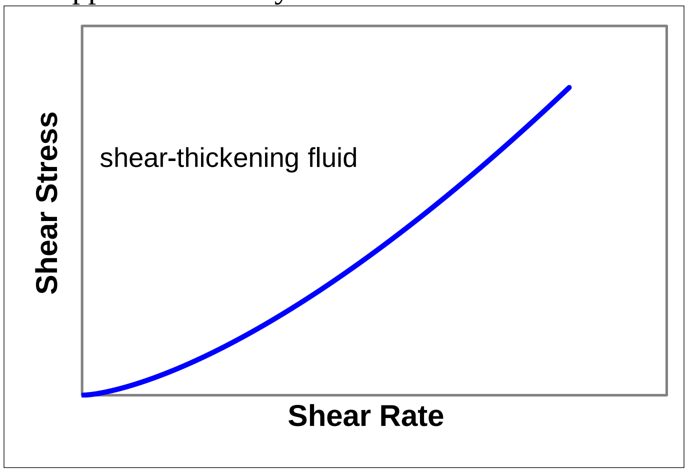
Upon using the connection among the shear stress, apparent viscosity, and the shear rate we get the power-law model.

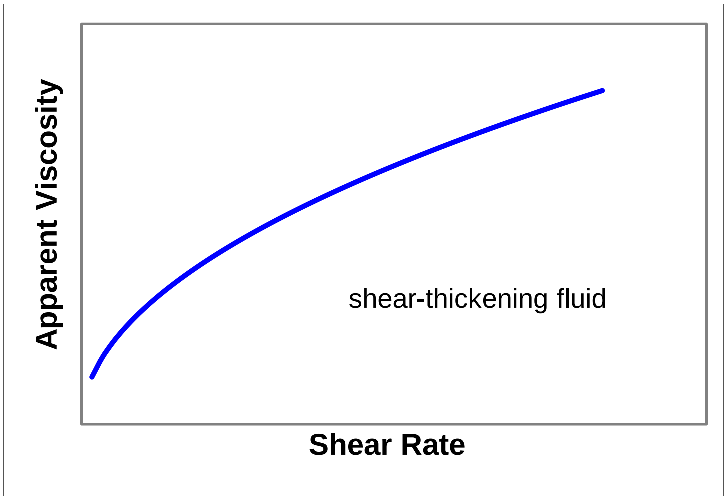
$$\tau = K\dot{\theta}^{n}$$

where n is called the power-law index. Note that $n=1$ corresponds to Newtonian behavior. Typically, for shear thinning fluids, n lies between $1/3$ and $1/2$, even though other values are possible.

Examples of shear-thinning fluids are polymer melts such as molten polystyrene, polymer solutions such as polyethylene oxide in water, and some paints. You can see that when paint is sheared with a brush, it flows comfortably, but when the shear stress is removed, its viscosity increases so that it no longer flows easily. Of course, the solvent evaporates soon and then the paint sticks to the surface. The behavior of paint is a bit more complex than this, because the viscosity changes with time at a given shear rate.

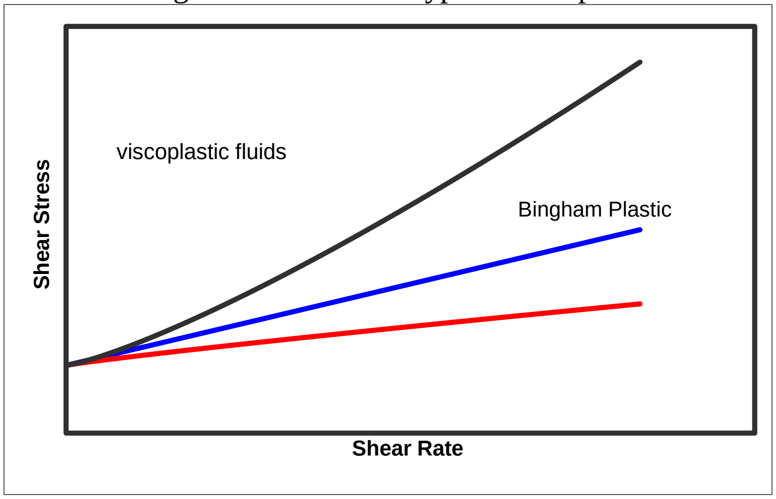
Some slurries and pastes exhibit an increase in apparent viscosity as the shear rate is increased. They are called shear-thickening or dilatant fluids. Typical plots of shear stress versus shear rate and apparent viscosity versus shear rate are shown in the two figures displayed next.





Some examples of shear-thickening fluids are corn starch, clay slurries, and solutions of certain surfactants. Most shear-thickening fluids tend to show shear-thinning at very low shear rates.

Another important type of non-Newtonian fluid is a viscoplastic or "yield stress" fluid. This is a fluid that will not flow when only a small shear stress is applied. The shear stress must exceed a critical value known as the yield stress τ_0 for the fluid to flow. For example, when you open a tube of toothpaste, it would be good if the paste does not flow at the application of the slightest amount of shear stress. We need to apply an adequate force before the toothpaste will start flowing. So, viscoplastic fluids behave like solids when the applied shear stress is less than the yield stress. Once it exceeds the yield stress, the viscoplastic fluid will flow just like an ordinary fluid. Bingham plastics are a special class of viscoplastic fluids that exhibit a linear behavior of shear stress against shear rate. Typical viscoplastic behaviors are illustrated in the next figure.



Examples of viscoplastic fluids are drilling mud, nuclear fuel slurries, mayonnaise, toothpaste, and blood. Also, some paints exhibit a yield stress.

Of course, this is not an exhaustive discussion of non-Newtonian behaviors. For instance, some classes of fluids exhibit time-dependent behavior. This means that even under a given constant shear rate, the viscosity may vary with time. The viscosity of a thixotropic liquid will decrease with time under a constant applied shear stress. However, when the stress is removed, the viscosity will gradually recover with time as well. Non-drip paints behave in this way. The opposite behavior, wherein the fluid increases in viscosity with time when a constant shear stress is applied is not as common, and such a fluid is called a rheopectic fluid.

Another important class of fluids exhibits viscoelastic behavior. This means that these fluids behave both as solids (elastic) and fluids (viscous). Viscoelastic fluids exhibit strange phenomena such as climbing up a rotating shaft, swelling when extruded out of a dye, etc. An example of a common viscoelastic liquid is egg-white. You have probably noticed that when it flows out of a container, you can use a quick jerking motion to snap it back into the container. Several industrially important polymer melts and solutions are viscoelastic. You can learn more about these and other behaviors from several fluid mechanics textbooks and from Perry's Chemical Engineers' Handbook. Also, you can visit some of the links on the course web page to You-Tube videos in which non-Newtonian behavior is demonstrated.