

PHYSICS FUNDAMENTALS-Viscosity and flow

The origin of viscosity

When a force is applied to a solid, it will yield slightly, and then resist further movement. However, when we apply force to a fluid, it continues to move away from the force, and we create a velocity gradient. Within a pipe, for example, the fluid in the centre moves faster than the fluid at the outside. Viscosity is the resistance to flow experienced as the internal layers of liquid move over each other.

Any kind of fluid, liquid or gas, has resistance to flow. This is caused at the molecular level by the drag between adjacent molecules. On a wider level, the flow of one layer of fluid against another is subject to 'drag', in the same way that surfaces in contact display friction when relative movement takes place.

Principle of measuring viscosity

The basic viscometer shown in Figure 1 has two plates separated by a thin layer of fluid. If you try to move one plate relative to the other, the liquid will exert a resistance. The higher the viscosity, the 'thicker' and more resistant to flow the liquid will be, and hence the slower the plate will move for a given force.

To achieve a constant speed, a constant force is applied. The force exerted by the weight acting over the pulley is described as a shear force, because it causes one plate to slide relative to the plate opposite. [Shear forces act over an area which is in line with the forces, in contrast to tension forces, where the plates are pulled apart, or compression forces, where the plates are pushed together]

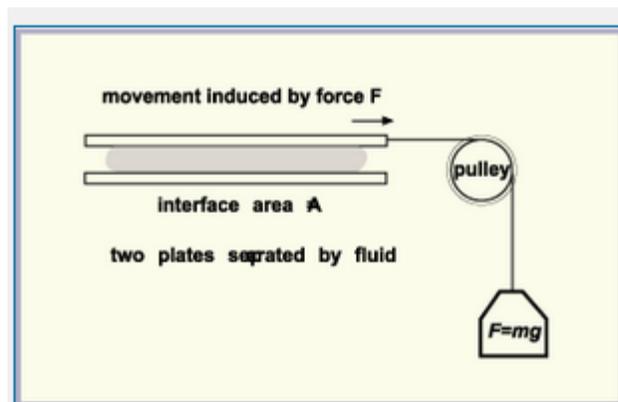


Figure 1: The principle of viscosity measurement

The shear stress is defined as the shear force per unit area of the interface, and given by the equation:

$$\text{shear stress} = \frac{F}{A}$$

Shear stress is measured in newtons per square meter (N.m⁻²) or its equivalent the pascal (Pa).

With a fluid between the plates, the shear force applied results in relative movement. As the force applied increases, so will the speed of the top plate. However, looking at the fluid between the plates we will find that there is a velocity gradient across the gap (Figure 2).

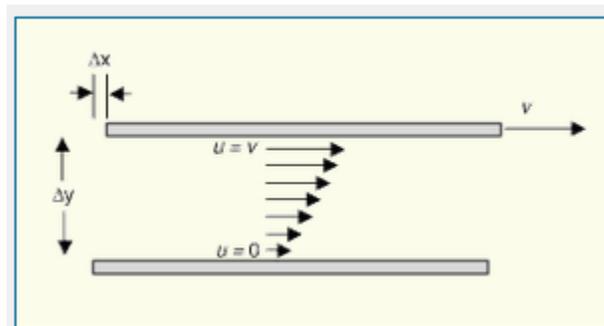


Figure 2: Detail of the fluid boundaries

This is because the fluid at the boundary is effectively 'attached to its plate' and constrained to move (or not move) at the same rate at the plate. The shear rate is defined as the velocity gradient, by the equation:

$$\text{shear rate} = \frac{v}{\Delta y} = \frac{\Delta x}{t \times \Delta y}$$

Shear rate is measured in meters per meter per second. However, as the first part is a ratio, the dimensions of shear rate are time⁻¹.

We define a coefficient of viscosity, normally abbreviated to viscosity, by the equation:

$$\text{viscosity} = \frac{\text{shear stress}}{\text{shear rate}} = \frac{F}{A} \times \frac{\Delta y}{\Delta x}$$

Viscosity is therefore measured in newtons per square meter per second (N.m⁻²s⁻¹).

As $1 \text{ N}\cdot\text{m}^{-2} = 1 \text{ pascal}$, we can also express viscosity in pascal-seconds $\text{Pa}\cdot\text{s}$, and this is the preferred SI unit. The symbol for viscosity varies between sources, but η (Greek letter eta) is the most common.

Many viscosity measurements still appear in older systems of units. In the cgs system, for example, the unit of viscosity is $\text{g}\cdot\text{cm}^{-1}\cdot\text{s}^{-1}$, called the poise (Po). However, this is a large unit: especially given that the viscosity of water at 20°C is about 0.01Po , the subdivision centipoise (cPo) was used more often, even when giving values for materials like solder paste which are typically quoted as 105 centipoise, rather than 103 poise.

Similarly, because the $\text{Pa}\cdot\text{s}$ is a large unit, viscosities are frequently given in units of $\text{mPa}\cdot\text{s}$. Even more helpful is the equality $1 \text{ cPo} = 1 \text{ mPa}\cdot\text{s}$ – plus ça change, plus c'est la même chose!

What we have been talking about is actually more correctly referred to as dynamic viscosity. An alternative measure is the kinematic viscosity, which is the dynamic viscosity divided by the density of the fluid. The conventional symbol for kinematic viscosity is ν (Greek letter nu), and its SI units are $\text{m}^{-2}\cdot\text{s}^{-1}$, but you will generally come across the cgs unit called the stoke ($10,000 \text{ stoke} = 1 \text{ m}^{-2}\cdot\text{s}^{-1}$). The continued use of this alternative comes from its ease of use for relatively thin fluids, measuring the time taken for a given volume of liquid to flow through a standard capillary tube, using one of several different standard instruments.

Yet another way of looking at the subject is to stand viscosity on its head, and use

the term fluidity ϕ (Greek letter phi), which is the inverse of viscosity: $\phi = \frac{1}{\eta}$

Flow behaviour of fluids

Newtonian fluids

So-called 'Newtonian' fluids have a resistance to flow which is constant, and the viscosity measured will be independent of the rate of flow (Figure 3). A simple example of such a fluid is water – the higher the pressure, the greater is the flow from the tap.

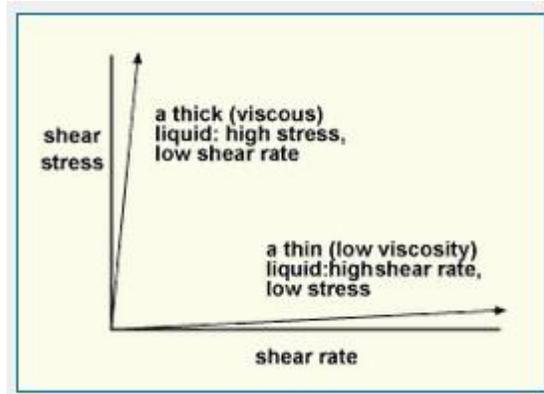


Figure 3: Fluid behaviour – Newtonian fluids

Whilst Newtonian fluids are common – water, petrol, beer – many other common materials have viscosities which are not constant. That is, their resistance to flow is not constant, and the flow rate which results when pressure is applied is not purely a function of the pressure gradient in the fluid.

As well as being non-linear when pressure is applied, fluids have viscosities that vary with temperature. As an example of a Newtonian fluid, think of how much easier it is to drain the oil from your sump if the engine is warm. Similarly, non-Newtonian materials such as solder paste invariably become less viscous as they warm up. Be aware that the rate at which viscosity falls off may not be constant, and that the reduction of viscosity will be particularly marked if one of the constituents in a pasty material melts.

Shear thinning

Real materials exhibit a variety of different behaviours, of which the most common is shear thinning¹. This describes the non-linear relationship between the rate at which force is applied and the resulting flow, where the fluidity increases with shear force (Figure 4).

¹ Such materials are referred to as exhibiting 'pseudoplastic' flow.

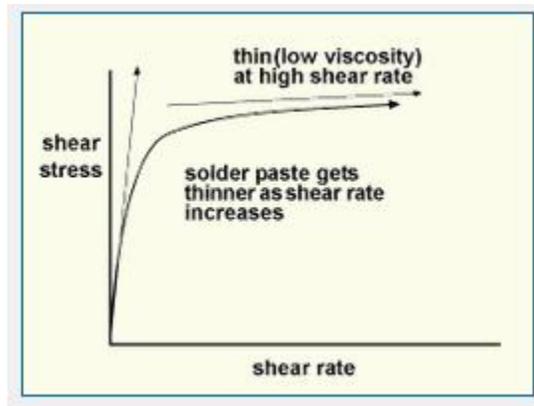


Figure 4: Fluid behaviour – shear thinning

A familiar material which is thinner at high rates of shear is tomato ketchup – remember how fluid this becomes when you shake the bottle vigorously! Another example is non-drip paint, where the force exerted by the brush acting against the surface being painted thins the material so that it flows, whilst removing the shear force leaves a material which (with luck) will not drip.

Such shear thinning is an essential requirement for printing: after all, we want to use paste which will flow into stencil apertures but remain in position without slumping.

Thixotropy

Solder pastes are not 'Newtonian' fluids: all pastes exhibit shear thinning, and most are thixotropic. Thixotropy is the term used to describe the 'memory' of a fluid, where the viscosity depends not just on the shear rate but also on the shear history of the paste.

You may remember from your DIY experiences that the one thing you don't do with non-drip paint is stir it before using, because this turns it, at least for a short period, into a material which is too thin to use. This 'memory' property is shared by solder cream, and a typical paste shows a lower viscosity with reducing shear rate – the paste is 'thinner on the way down' (Figure 5).

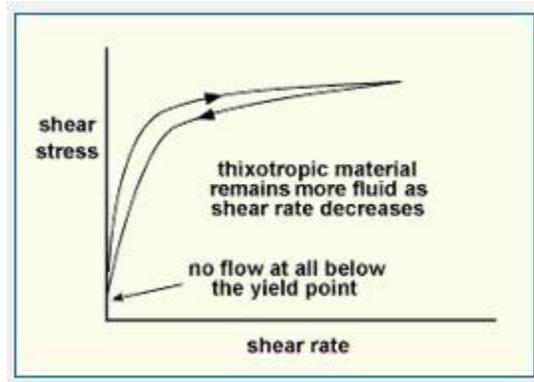


Figure 5: Fluid behaviour – thixotropy

There is always a 'knee' in the shear stress : shear rate curve for all materials which exhibit shear thinning (Figure 4). Materials which are thixotropic have a second feature: there is often a yield point, a minimum shear stress below which the cream does not move (Figure 5). This ensures that the material will not slump during use or separate during transport and storage. If a cream is too thick, because it does not shear thin, or has too high a yield point, it will be difficult to print.

Caution

A common method for characterizing and quantifying non-Newtonian flow is to quote the ratio of the fluid's viscosity as measured at two different speeds, usually differing by a factor of 10. This procedure is commonly known as the 'thixotropic index'. The name is, however, misleading since this ratio measures time-independent non-Newtonian behaviour, whereas thixotropy is a time-dependent phenomenon.

Rheology

So far we have considered viscosity as a measure of the ratio of shear stress to shear rate and one that varies with stress in a non-Newtonian fluid, which may exhibit shear thinning and thixotropy. If you are interested in this topic of flow, then even the most cursory look at a text book will indicate that other fluids have other types of non-linear behaviour.

We use the term 'rheology' broadly, to represent the way that a fluid flows and deforms under a given set of conditions, such as temperature or force. Measuring the rheological behaviour of a material is actually what we are measuring when we use a viscometer – the measurement taken is of stress : rate, or its inverse, but the results that we get depend on the type of equipment, the way it is used, and on factors such as temperature and the flow history of the material.

This is a complex topic, which we will only overview in the next section. There are those who would say that to try to standardise tests for this behaviour is less useful than a practical assessment of whether or not the material will perform in the manner needed. However, given the variation in the way that materials are used, suppliers are likely to continue to aim at reproducible tests.

Practical measures of viscosity

For Newtonian fluids, there are many ways to measure viscosity, including the standard tests referred to earlier, which measure how fast a fluid flows through a tube. Another easy way, applicable to transparent media of moderate viscosity (up to 50Pa·s, is to see how fast a sphere falls through the fluid. A fluid with high viscosity resists flow, so the sphere falls slowly; if the fluid has a low viscosity, it offers less resistance to flow, so the ball falls faster.

The measurement is generally carried by timing each sphere as it traverses a measured distance, repeating the tests many times to arrive at a meaningful average value and, from the scatter in the results, at an assessment of the measurement certainty.

It is probably simplest to carry out comparative tests, and calculate the viscosity from the formula:

$$\eta = K \times (\rho_s - \rho_f) \times t$$

Where:

h = viscosity

K = viscometer constant

rs = density of ball

rf = specific gravity of the liquid

t = time of descent

The viscometer constant is calibrated using known materials, such as deionised water. Where spheres of very accurate dimension and density are available, it is also possible to calculate absolute values of viscosity from Stokes' Law, which relates the shear stress to the balance of weight, drag and buoyancy forces and the shear rate to the terminal velocity in the fluid.

Measuring viscous materials

For viscous materials such as solder paste, adhesives, solder mask or legend ink, rotational viscometry is the most used of a number of generic techniques that are available to measure the rheological behaviour. The sensors adopted are cone-and-plate or plate-and-plate designs as shown in Figure 6. The torque required to drive the cone or plate is measured, and plotted against the corresponding rotational speed to show the shear stress (viscosity) to shear rate relationship of the medium.

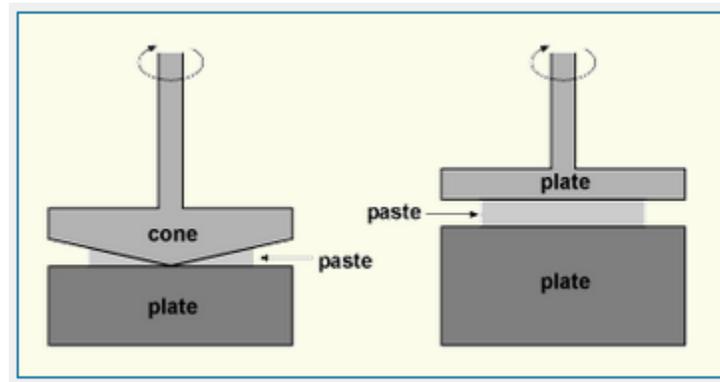


Figure 6: Cone and plate methods of rotational viscometry

These instruments use the fact that viscous fluids which contain long-chain polymers are not drawn to the outer surface by centrifugal force, but tend to move to the centre because of the Weissenberg effect.

Flow properties are generally not easy to measure, and it is particularly difficult to draw conclusions from measurements made in different ways. Also, single point viscosity measurements, however simple and convenient to carry out, cannot be used to characterise solder creams, because different materials may shear thin by different amounts, their yield points may vary, and they may exhibit differing degrees of thixotropy. At best, single point measurements are valid only when:

the rheology of the paste is known

the paste handling technique immediately prior to measurement is standardised

the measurement technique of the paste is standardised.

The viscosity characteristic is more usually displayed on a flow curve or rheogram, which plots shear stress against shear rate, measured continuously as the shear stress first increases and then decreases. The basis of many commercial instruments is the configuration shown in Figure 7, where the solder paste can be kept in its own container and a spindle immersed to a known depth. In the more

common configuration of the right-hand diagram, the spindle with a paddle attached executes a number of axial rotations on a helical path, so that the paste being contacted is constantly changing.

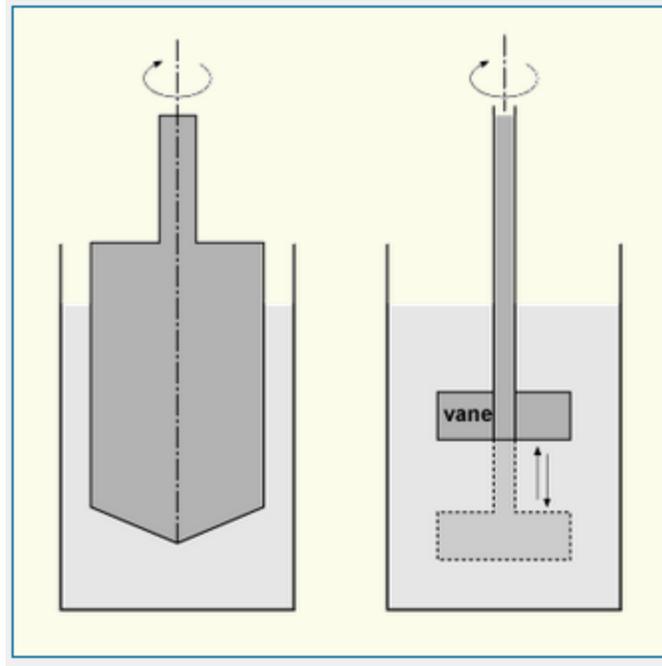


Figure 7: Schematic configurations of viscometers suitable for solder paste

Viscosity changes with temperature², and it is therefore crucial that viscosity measurements are made at a constant temperature: 25°C is the usual choice for reference temperature, although this may not be representative of conditions in Far Eastern assembly plants.

² Because the rate of molecular interchange increases with temperature, the drag force on a moving body might be expected to increase in the same way, and in fact the viscosity of a gas goes up with temperature. However, in a liquid, the van der Waal attraction is responsible for much of the drag, and that reduces with temperature as individual atoms become more mobile.

Alternative measurement techniques

An entirely different approach for comparing viscosities of solder pastes or adhesive is to try them in the intended application. Measures of dispensability and printability are not easy to standardise, but are useful for the pragmatist.

In the nozzle flow method, the paste is dispensed at different defined pressures onto a glass slide. The weight of paste deposited is an arbitrary but relevant measure of viscosity and the test is appropriate to pastes intended for dispensing rather than screen printing.

In a typical test: the glass slide is weighed; the needle length and internal diameter are defined (15mm and 840 μ m or 510 μ m respectively being standard); a set pressure (1, 2, 3, or 4 bar) is exerted on the piston for ten seconds; the slide is then reweighed.

A paste that is designed to be printed has good printability (or 'screenability') if the proper wet height, coverage and edge resolution are maintained on the printed substrate. Printability of a paste includes such subjective evaluations as how easy it is to print, and how well the solder paste spreads.

Although in many ways a qualitative assessment of the solder paste, attempts have been made to define the properties that ensure good screenability. The shearing rate of the paste can be calculated from the squeegee speed, and the properties of the screen and its emulsion. Knowing the shear rate, the shear stress can be determined using a viscometer. For the paste to screen well, the shear stress needs to be less than 3 N \cdot cm⁻².

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Source: http://www.ami.ac.uk/courses/topics/0208_vaf/index.html