Viscosity Measurement Guide

For using Viscotester

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Introduction

This little guide is intended to provide some general background information that may be helpful before starting to use the Viscotester. The guide first provides an overview of the concept of viscosity and then touches upon topics such as how the pascal-seconds unit is defined, what types of viscosity there are, what other kinds of viscosity measuring devices are used and how they compare to a Viscotester.

What is viscosity?

As illustrated by Figure 1, when some jelly is placed between two plates, a force will be required if one attempts to separate the plates by pulling them horizontally in opposite directions. This is due to the **viscosity** of the jelly. The thicker the consistency of the jelly, the more force will be required, as the thicker jelly is more **sticky**, or in other words, it has a **higher viscosity**. The property of viscosity means that when there is relative velocity between two adjacent portions or sections of a fluid, a resistance to the motion will be present. The section whose velocity is faster will accelerate the neighboring slower section, and conversely, the slower section will decelerate the faster section.

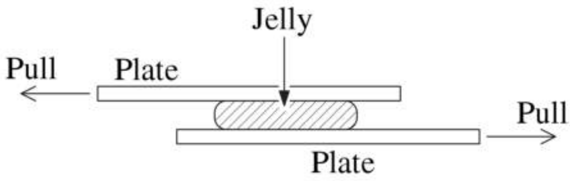

Figure 1

When the property of being sticky or tacky is expressed in numeric terms, we have **viscosity**. But how was this concept defined?

In Figure 2, the space between the surfaces of two parallel plates is filled with a fluid. Surface (2) is stationary, while surface (1) is moving in the arrow direction at a constant speed (velocity) expressed by v.

The distance a between the two surfaces is constant, and it is assumed that the section of the fluid in contact with the surface adheres to and moves together with it. Therefore the velocity of the respective sections of the fluid is v at surface (1) and 0 at surface (2).

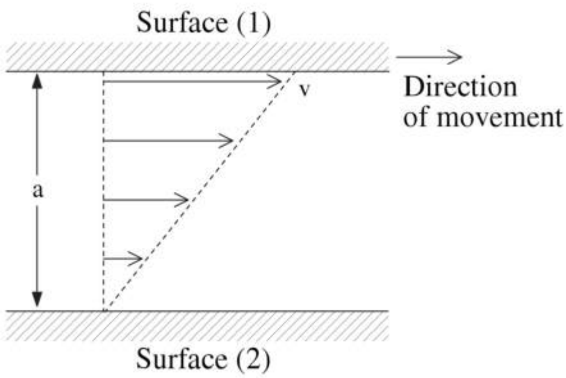

Figure 2

Furthermore, provided that the velocity is relatively low, so that no eddies are formed, the fluid will flow in layered sections that are parallel to the enclosing surfaces, and the velocity increases proportionally with the distance from surface (2). This velocity distribution is shown by the dotted line in the Figure 2.

As the velocity changes from 0 to v over the distance a, we can take the change in velocity per unit of distance as D, and the following applies:

$$D = \frac{v}{a} \qquad \text{The unit is } s^{-1}$$

Consequently, D is a quantity expressing the gradient of the velocity. The larger the value of D, the faster the velocity change. This quantity of D is called the **shear rate**.

As mentioned above, when there is a velocity gradient in the fluid, the faster section exerts an accelerating force on the adjacent slower section (or the slower section a decelerating force on the adjacent faster section). This force is due to viscosity. The force F is proportional to the shear rate D, and also to the surface area A of the two adjacent layers. Expressed as an equation, the relationship is as follows.

$$F = \eta AD$$

The proportionality constant η in this equation is the **viscosity**, also called the **coefficient of viscosity**. The equation is called **Newton's law of viscosity**. When the shear rate D and the contact surface area A are constant, the force exerted on the contact surface will increase towards higher values of the viscosity η. Consequently, the higher the viscosity η, the more viscous the fluid. η can therefore be used as a numeric quantity to express the viscosity of a fluid.

Viscosity unit: pascal-seconds

The unit used to express viscosity is called **pascal-seconds**, with the unit symbol Pa•s. When the viscosity of a fluid is 1 decipascal-second and the velocity change is 1 cm/s per centimeter, the shear rate D will be 1 s^{-1}.
At this shear rate of D=1 s^{-1}, the force acting on the surface unit of 1 square centimeter, or 1 cm^2 is 10^{-5} N. At a viscosity of 10 decipascal-second, the force will be 10 times higher than the value above.
1/100 of 1 decipascal-second is called 1 millipascal-second (mPa•s).

100 mPa•s = 1 dPa•s

To give a practical example, the viscosity of water is approximately 1 mPa•s (at 20°C), and that of rapeseed oil is approximately 1 dPa•s (at 15°C).

Kinematic viscosity unit: square meter per second

The viscosity η divided by the density ρ of the liquid is called **kinematic viscosity** ($V = \eta / \rho$). The unit is **square meters per second**, with the unit symbol m^2/s. Viscosity as measured with a capillary tube viscometer (such as an Ostwald viscometer) or a short-tube viscometer (such as a Ford cup) is the kinematic viscosity (square meters per second). In order to calculate the viscosity (pascal-seconds) from kinematic viscosity, the density must be measured separately and multiplied with the kinematic viscosity value.

$$\eta = \rho V$$

1/100 of 1 square centimeter per second is called 1 square millimeter per second (mm^2/s).

$$100\ mm^2/s = 1\ cm^2/s$$

Newtonian fluids and non-Newtonian fluids

Newton's law of viscosity equation

$$F = \eta AD \qquad (1)$$

Because the force F in equation (1) works on the area A, it can be rewritten to equation (2) as the force τ per unit of area. This gives

$$\tau = \frac{F}{A} \qquad (2)$$

τ is called the shear force.
Using τ, we can rewrite the viscosity equation (1) as follows

$$\tau = \eta D \qquad (3)$$

Alternatively,

$$\eta = \frac{\tau}{D} \qquad (4)$$

Expressed in common language, this is

Viscosity = Shear force / Shear rate

Figure 3 shows the relationship of equation (3) as a graph. Fluids where the relationship between τ and D is linear are called **Newtonian fluids**. The steeper the slope of the straight line, the higher the viscosity.

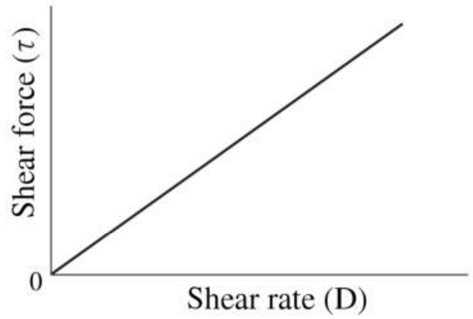

Figure 3

However, among fluids with high viscosity, there are many where the relationship between τ and D is not linear. These are called non-Newtonian fluids because Newton's law of viscosity does not hold for them. Figure 4 shows various examples of such **non-Newtonian fluids**, with their τ to D relationship.

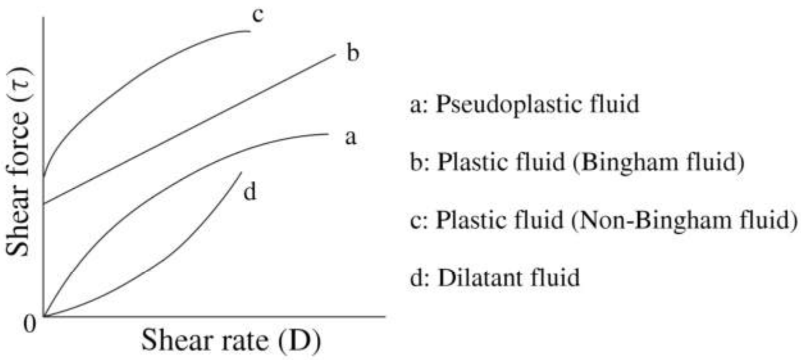

Figure 4

(a) represents a pseudoplastic fluid which is characterized by the fact that its viscosity decreases at higher values of shear rate D. (b) represents a plastic fluid (Bingham fluid) that only starts to flow when the shear force exceeds a certain threshold. After the flow has begun, the τ to D relationship is linear. The value of τ where flow motion starts is called the yield value.
(c) is similar to (b), but it is a plastic fluid (non-Bingham fluid) where the τ to D relationship does not become linear.
With (d), the τ to D relationship is opposite to that of (a), which is the behavior of a so-called dilatant fluid.
The curves in Figure 4 are referred to as **flow curves**.

Apparent viscosity

As will be explained later in this guide, there are many different types of viscometers. Different viscometer will also use different shear rates.

For Newtonian fluids, viscosity does not change at different shear rates, and the measurement values obtained with different viscometers therefore will not differ greatly.

With Non-Newtonian fluids however, as is apparent from Figure 4, the shear force is not proportional to the shear rate, and viscosity therefore will change when the shear rate D is different. Consequently, the type of viscometer or the measurement setup will influence the viscosity values that are obtained. This is called **apparent viscosity**. The apparent viscosity applies to a given viscometer or to a given shear rate.

The degree of change in viscosity according to the shear rate varies depending on the kind of fluid. If the apparent viscosity measured for two different fluids is measured at a given shear rate and the values are found to be equal,

they may turn out to be completely different when measured with a different shear rate. In other words, the viscosity reading for Non-Newtonian fluids will vary depending on the viscometer.
This will be illustrated with measurement examples on page 24.

Viscosity changes with temperature

As the three examples below for water, mercury, and glycerine show, viscosity values can also be temperature-dependent. While mercury stays relatively constant, the viscosity of water shows a noticeable change, and glycerine is in a completely different range at different temperatures. In extreme cases, a change by one degree centigrade may result in a viscosity that is several times higher or lower.
Therefore the temperature should always be measured as well when making a viscosity measurement.

Viscosity change by temperature

Temperature	Water	Mercury	Glycerine
0°C	0.018 dPa•s	0.017 dPa•s	121 dPa•s
20°C	0.010 dPa•s	0.016 dPa•s	15 dPa•s
100°C	0.0028 dPa•s	0.012 dPa•s	-

Viscosity changes over time

With some fluids, viscosity will drop steadily as the fluid is stirred, and will return to the former value when the fluid is left at rest for a certain time. Such fluids are referred to as **thixotropic fluids**.
By contrast, there are also cases where stirring will result in increased viscosity which then drops when the fluid is at rest. With some fluids, stirring will decrease viscosity which then does not return to the former value (**aging**).
For these special types of fluids, it is not possible to determine a single viscosity, but the Viscotester allows observing the changing conditions in real time, because it is a direct-reading instrument.

Types of viscometers

Viscometers come in many different kinds. The most commonly used types by operation principle are listed below.

Capillary tube viscometer

Principle: Sample fluid is passed through a capillary tube made of glass, and the time it takes for a certain volume to pass is measured.

Features:
(1) High accuracy
(2) Measurement range normally within several thousand mm^2/s
(3) Kinematic viscosity (mm^2/s) can be read directly

Examples: Ostwald, Ubbelohde, Reverse flow (Cannon-Fenske)

Short-tube viscometer

Principle — At the base of a container, a short tube is attached for the liquid to flow through, and the time it takes for a certain volume to pass through is measured.

Features
(1) Simple construction, easy handling
(2) Measurement range from several mm^2/s to several thousand mm^2/s
(3) Kinematic viscosity can be determined using a conversion table

Examples — Redwood, Saybolt, Engler, Ford cup

Falling body viscometer

Principle	The sample is filled into a glass tube, and the time it takes for a sphere or cylinder to descend through it is measured.
Features	(1) If the sphere is made small enough, measurement of 10 dPa•s or higher is also possible (2) Density must be measured separately
Examples	Lawaczek

Falling ball viscometer

Principle: The sample is filled into a tilted glass tube, and the time it takes for a ball to roll through it is measured.

Features:
(1) Precise measurement of several thousand mPa•s or lower is possible
(2) Density must be measured separately

Examples: Höppler

Bubble viscometer

Principle: The sample fluid is enclosed in a test tube together with a given volume of air. The tube is then overturned and the speed by which the bubble rises is compared to a reference tube.

Features:
(1) Easy handling
(2) Convenient for a quick estimate of viscosity

Dual concentric cylinder rotational viscometer

Principle: The sample is introduced between the inner and outer cylinder. One of these is made to rotate at a constant speed, and the torque acting on the other cylinder is measured.

Features:
(1) Convenient for measurement of 10 dPa•s or higher
(2) Non-Newtonian flow can be checked

Examples: Stormer, Green, MacMichael, Universal Rheometer

Uni-cylinder rotational viscometer

Principle: A single cylinder is made to rotate at a constant speed in the sample fluid and the torque is measured.

Features:
(1) Convenient for measurement of several 10 mPa•s or higher
(2) Hand-held use is possible, enabling measurement without retrieving sample from a tank or similar

Examples: B type viscometer, Viscotester

Cone and plate viscometer

Principle: The sample fluid is introduced between a cone and a flat plate. One of these is made to rotate and the torque at the other element is measured.

Features:
(1) High accuracy
(2) Convenient for high viscosity measurement
(3) Non-Newtonian flow can be checked

Other types

Besides listed types, there are also vibrational viscometers, parallel plate viscometers, float viscometers, etc.

Conversion

For Non-Newtonian fluids, measurement values obtained with different types of viscometers cannot be converted. For Newtonian fluids, tables for converting flow-out time measured with a short-tube viscometer into kinematic viscosity are available. For example, the values corresponding to 3 square centimeters per second with various types of short-tube viscometers are as follows.

3 square centimeters per second = approx. 1400 Saybolt seconds
= approx. 1200 Redwood seconds
= approx. 80 Ford cup seconds
= approx. 40 Engler degrees

Multiplying the square meters per second value with the density of the fluid gives pascal-seconds.

Because the No. 1 rotor of the Viscotester can measure viscosity of 3 dPa•s or higher, it can be considered suitable for measuring approximately the above seconds values and higher.

Viscotesters

Viscotesters are uni-cylinder rotational viscometers. They belong to the category of B type viscometers, but have been designed to provide direct readout in decipascal-seconds or millipascal-seconds which is the most practical unit for use in the field, and the revolution speed switching function has been eliminated.

The shear rate is about 13 s^{-1} with the No. 1 rotor and about 4 s^{-1} with the No. 2 rotor. Therefore viscosity readings may change when the rotor is changed. This will occur when the fluid is a Non-Newtonian fluid, causing the apparent viscosity to change when the shear rate is different. It is not a defect of the Viscotester.

Measurement examples

As explained earlier, many liquids with high viscosity are Non-Newtonian fluids. Some examples of Non-Newtonian fluid flow curves measured with a cone and plate viscometer are shown in Figure 5.

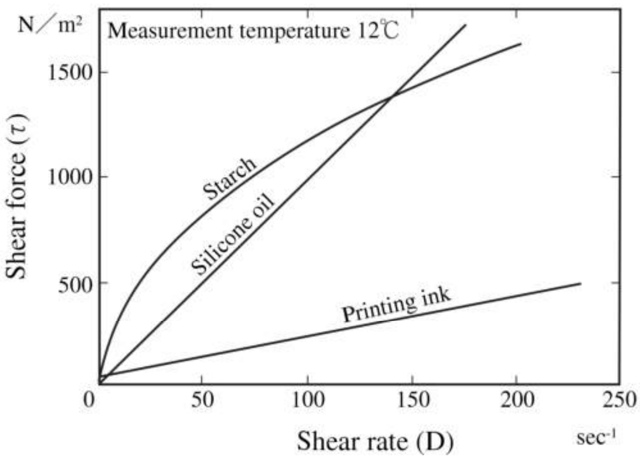

Figure 5 Flow curves

Plastic fluids such as starch and printing ink will not begin to flow until the shear force τ reaches a certain value f (yield value). The shear rate D therefore is 0 up to this point. When the shear force exceeds f, a flow motion occurs. As τ increases, D shows a sudden rise.
With silicone oil, τ - D is roughly linear, so that it can be considered a Newtonian fluid.
The ratio between the shear force τ and the shear rate D for each point on the flow curve is the apparent viscosity ηa. ηa changes according to the shear rate D, as shown in Figure 6.
In Figure 6, the apparent viscosity for silicone oil does not change with D, because it can be considered a Newtonian fluid. For starch and printing ink, however, the apparent viscosity ηa decreases as D gets larger, because these are Non-Newtonian fluids.

The shear rate D will always be different in various viscometers. With a capillary tube viscometer for example, D is determined by the time duration of the flow of the sample as well as by the dimensions of the capillary tube. With a rotational viscometer, the revolution speed of the rotor and its shape are the determining factors for D.
A comparison between a Viscotester with No. 1 rotor and a B type viscometer when the revolution speed is varied over a range of 6 to 60 is shown below. Observing the curve for printing ink in Figure 6, the apparent viscosity measured by the B type viscometer with a revolution speed of 60 is 43 dPa•s, which is about 1/3 of the 130 dPa•s measured with a revolution speed of 6. Because revolution speed of the Viscotester's No. 1 rotor is 62.5, the apparent viscosity measured by the Viscotester's No. 1 rotor and the apparent viscosity measured by the B type viscometer with a revolution speed of 60 is almost same value.

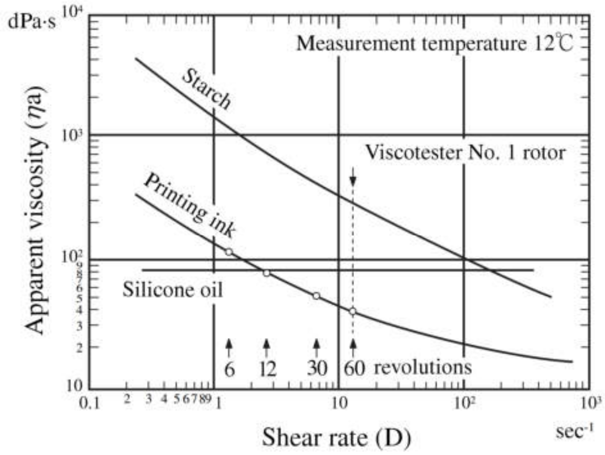

Figure 6 Change in viscosity dependent on shear rate D

With silicone oil, the viscosity does not change according to the revolution speed. The apparent viscosity of silicone oil measured with the Viscotester's No. 1 rotor is about twice as high as that of printing ink, but when measured by the B type viscometer with the revolution speed of 12, the apparent viscosity values are approximately equal.

The example which measured the viscosity of the samples used in the household by Viscotester are listed below.

Viscotester measurement examples (temperature is 23°C)

Product name	Viscosity	Viscotester	Rotor
Newtonian fluids			
Milk	2.6 mPa•s	VT-05	No. 4
Soy sauce	5 mPa•s	VT-05	No. 4
Lactobacillus beverage	28 mPa•s	VT-05	No. 5
Olive oil	71 mPa•s	VT-05	No. 5
Castor oil	6 dPa•s	VT-06	No. 3
Starch syrup	1000 dPa•s	VT-06	No. 2
Non-Newtonian fluids			
Tomato juice	230 mPa•s	VT-05	No. 3
Condensed milk	16 dPa•s	VT-06	No. 1
Chocolate syrup	25 dPa•s	VT-06	No. 1
Tomato ketchup	43 dPa•s	VT-06	No. 1
Honey	76 dPa•s	VT-06	No. 1
Toothpaste	320 dPa•s	VT-06	No. 2
Starch glue	310 dPa•s	VT-06	No. 2