Article for the 23rd Sensing Forum

Theme: Physical Quantity Measured by a Vibration Viscometer

(Re: JCSS Standardization of Viscosity)

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Physical Quantity Measured by a Vibration Viscometer

Subtitle: The JCSS Standardization of Viscosity

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Abstract

The objective of this article is to introduce a viscometer that utilizes a new viscosimetry measuring method. In addition, the article will recommend a new unit system, which is utilized in the vibration viscometer. Using examples, the article explains JCSS viscosity standardization and recent requirements for viscosity measurements.

Keywords: Vibration Viscometer, Static Viscosity (Viscosity × Density), Viscosity JCSS, Cloud Point

Introduction

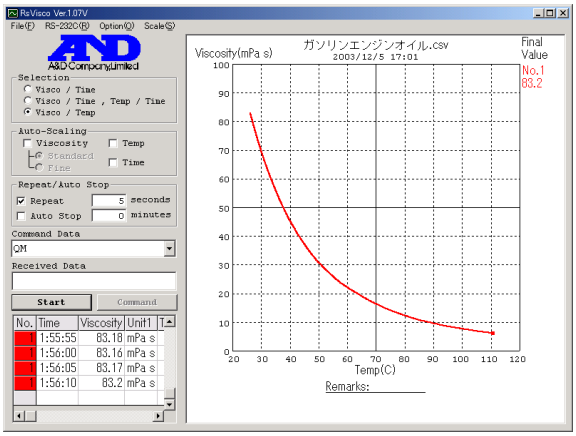
The following is an introduction of the vibration viscometer, a new method for measuring viscosity. In addition to providing a description of the physical quantity that is measured using the vibration viscometer, a new unit system for viscosity will be proposed. Furthermore, there is an explanation regarding the Japan Calibration Service System (JCSS) standardization of viscosity and viscosity measurements using actual examples. There is also discussion of recent requirements for measuring viscosity.

History and Development of Viscosity Measurement

The history of viscosity measurements is extensive and is believed to date back to when people began measuring the viscosities of engine oils with the advent of the automobile industry in the United States. In the U.S., it had become necessary to control the viscosities of engine oils as a method of maintaining the performance of engines. Even today, viscosities of engine oils are standardized for both high and low temperatures, such as 5W-30. It is believed that if the viscosity of oil reaches below 2.6 cp (the viscosity of purified water at 20˚C is approximately 1 cp = 1 mPa·s : 1 milliPascal second) the engine will burn out. This has recently become an important issue when developing energy-saving engine oils for the purpose of improving fuel efficiency. Furthermore, the demand for viscosity measurements aimed at maintaining quality in the field of cutting-edge technologies has been increasing. This is due in part to the expansion of new markets for viscosity-related applications, which now include resist inks for liquid

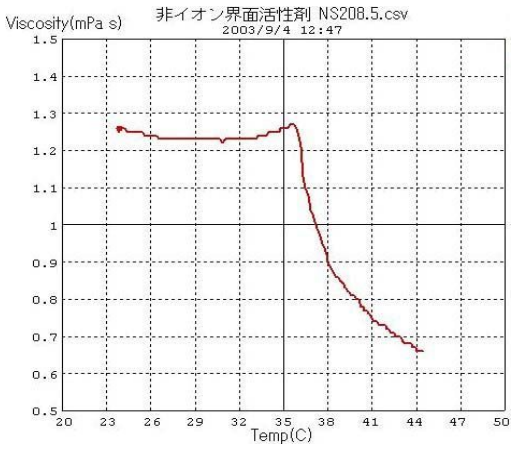
crystals, abrasives for semi-conductors, glass coating materials, powder particle size distribution, polymeric emulsion and cloud point measurement of surface-active agents. Moreover, recently there have been discussions of performing viscosity measurements of human blood. Studies have shown that high blood viscosity increases the possibility of sudden death due to diseases affecting the circulatory system. The viscosity of human blood, although dependent on the measurement method, is generally believed to fall somewhere between approximately 3 and 10 mPa·s.

Actual examples of the measurements of the viscosity and temperature of engine oil and cloud point measurements of nonionic surface-active agents have been presented in Figures 1 and 2 for reference.



Viscosity change of gasoline engine oil

Figure 1.



Cloud point measurement

Figure 2.

Definition of Viscosity and the JCSS Standardization

Viscosity is defined using the relative motion between two boards that have been placed opposite to each other in a sample liquid. Viscosity is the proportional constant when the interactive force (shear stress) per unit area generated in the planar direction between the opposing two boards, and the velocity gradient (shear rate), calculated by dividing the relative displacement speed by the distance between the two boards, are proportional. Based on this definition, there is a proportional relationship between the shear stress and the shear rate. The fluid is called a Newtonian fluid in the event that the shear stress and the shear rate are proportional, and viscosity is indicated as a constant stable value. On the other hand, if the proportional relationship with the shear

stress deteriorates due to changes in the shear rate or if the proportional relationship is lost due to temporal changes (a fixed viscosity value cannot be determined for the liquid due to the measurement conditions), all such fluids are collectively called non-Newtonian fluids. While as demonstrated above, it is easy to define viscosity, the structures of the devices to conduct actual measurements are not as simple and there are many structural problems. For example, it is important to stabilize the measuring environments, such as keeping the measuring temperature constant, for methods like the cup type, which measures the time taken by the sample liquid to flow from the opening of a given sample cup, the falling-sphere type, which measures the viscosity by the time needed for a rigid body to fall within the sample liquid, and the capillary type, which measures the time taken by the sample liquid to flow inside a capillary. For the rotation type, it is necessary to regulate the rotation of a rotor at a constant speed and steadily measure the torque required for the rotation. On the other hand, for the vibration type, which calculates the viscosity from the power to drive an oscillator placed in a sample liquid, technology to steadily vibrate the oscillator at the natural frequency is essential. Among viscosity measurements based on the measurement principles above, the underlying theory of the measurement principle that has become the modeling formula (modeling equation) and the “uncertainties” inherent in the measurements have been demonstrated with the capillary, rotation and vibration types. As a result, along with the standard liquids of viscosity, these types of viscometers were accredited as the JCSS standard devices and have been uploaded to the official website of the National Institute of Technology and Evaluation (NITE) as of April 2006.

Physical Quantity Measured by Each Measurement Method

Next is a brief explanation of the measurement principles for viscosity standardized by the JCSS:

Capillary type: A liquid filling a given vessel is made to flow to a lower position by gravity and the viscous behavior of the liquid is measured based on the flow time. The time taken by the liquid for the movement is measured and is converted to a viscosity value using the flow time of internationally standardized water as a reference. When using this measurement principle, the physical quantity to be measured (i.e. time) is proportional to the viscosity, but inversely proportional to density. Therefore, this physical quantity can be expressed as “viscosity/density,” and is called the “kinetic viscosity.”

Rotation type: A rotor is placed in a liquid and is constantly rotated. During rotation,

the torque necessary for the rotation is proportional to the viscosity. The “viscosity” is the physical quantity that is measured.

Vibration type: An oscillator placed in a liquid is vibrated at a constant displacement magnitude. By detecting the power necessary for the vibration, the viscous behavior of the liquid is measured. The physical quantity to be measured is expressed as “viscosity × density.”

Advantages and Measurement Principles of the Vibration Viscometers

There are two kinds of vibration viscometers, the rotational vibration type and the tuning-fork vibration type – both types rely on the same measurement principle. The present section is devoted to a detailed explanation of the tuning fork vibration method. A viscometer using the tuning-fork method has a pair of opposing oscillators of the same natural frequency. Each of these oscillators is individually synchronized and driven by electromagnetic power. As the two oscillators move in opposite phases, no outward reactive force is generated: this is true with a tuning fork. Driving at a natural frequency with very small damping is also possible. During the viscosity measurement, the amplitude that is generated is constantly measured and controlled in order to maintain a fixed amplitude. In addition, the electromagnetic power required to drive the oscillators is also measured. Viscosity is determined based on variations in driving power in accordance with viscosity multiplied by the density of the liquid in which the oscillators are immersed. The energy applied to the sample liquid is small because the vibration method causes only minute displacement in the sample liquid. Moreover, as the thermal capacity of the oscillator is small, interference to the sample substance due to the measurement can be minimized. Since there is no flowing or churning of the sample liquid, little change is caused mechanically to the physical properties of the sample even after the measurement starts, making a speedy and stable measurement possible. The viscosity of a liquid is temperature dependent and varies by as much as –2 ~ –10%/˚C. Hence, small interference by the measuring system can provide benefits such as decreasing the possibility of temperature variation that can cause changes to the physical properties of the sample. In addition, by utilizing a tuning-fork vibration, the viscometer has a high measurement sensitivity and is capable of performing continuous measurements, ranging from as low as 0.3 mPa·s (1/3 the viscosity of purified water) to 10,000 mPa·s. This enables the measurement of the cure processes of materials such as adhesives, gelatin, and egg albumen. For example, the cure processes of albumen proteins with different constituents can be monitored at different temperatures. The physical quantity measured by the vibration viscometer is, from the

theoretical formula, “viscosity × density” in principle.

Next, is an explanation of the measurement model for the tuning-fork vibration viscometers. As illustrated in the model of the free vibration system shown in Figure 3, inertia terms based on the mass of the measuring system, viscous terms based on the viscosity of the liquid, and the spring terms based on the spring constant of the measuring system can be examined. When the measuring system is driven by electromagnetic power at the natural frequency determined by the mass and spring constant of the measuring system, the inertial force and the restorative force of the spring will balance each other, and the energy consumed by the measuring system will only be the viscous term of the liquid. This information is presented in Formula (1) expressed as a motion equation, where F: Excitation force, m: Mass, C: Viscosity coefficient, K: Spring constant, x: Amplitude, ωn: Natural frequency of the vibration system

$$F = m\frac{d^2x}{dt^2} + c\frac{dx}{dt} + Kx \quad (1)$$

When Expression (1) is integrated,

$$x = \frac{F}{c\,\omega_n} \quad (2)$$

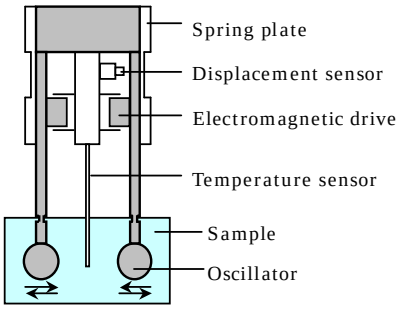


Figure 3. Mechanism of the detection system

If the amplitude (displacement magnitude) x and the natural frequency ωn are constant values, there should be a proportional relationship between the excitation force F and the viscosity coefficient C. By applying this principle, the tuning-fork vibration viscometer resonates the two oscillators at the natural frequency with electromagnetic power and thus realizes highly sensitive viscosity measurements.

Examination of the Unit System for Viscosity

The measurement principles of the capillary and the rotation viscometers are comparatively simple and have a long history of being used for measurements. Hence, the “kinetic viscosity” and the “viscosity” have long been acknowledged as the unit systems suitable for these types of viscometers. Theoretically, the measurement principle for the vibration viscometer

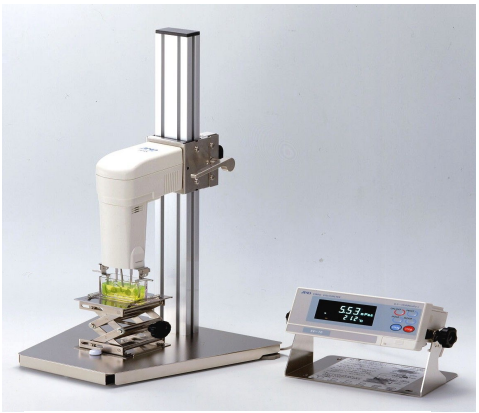


Figure 4. Vibration viscometer

was established in Japan approximately half a century ago. It was featured in publications in Japan as early as 1958 and was expected to become a new method to conduct viscosity measurements. However, because technology to drive oscillators at the natural frequency was difficult, the vibration method did not see its way onto the market for many years.

Today, despite the fact that the production technology has become feasible and the product has already been introduced to the market, the “viscosity × density” unit system has not yet been officially adopted. Therefore, I would like to propose the adoption of “static viscosity” as the physical quantity for the vibration type, similar to “kinetic viscosity” for the capillary type and “viscosity” for the rotation type. The reasons for my proposal are as follows:

- The “kinetic viscosity” (viscosity/density) of the capillary type can be obtained by measuring the time taken by a liquid in a vessel of a given volume to go through a flow channel of a given diameter. Consequently, the physical quantity to be obtained is in direct proportion to the viscosity while inversely proportional to the density, which generates the pressure to the fluid. Meanwhile, this measurement method is accompanied by a barycenter shift of the liquid as the liquid being measured actually flows through the inside of the tube. The kinetic viscosity is an indication of this state of the liquid and can be considered to be accurate.

- In the rotation viscometer, although the liquid is in rotational movement, there is no shifting of the liquid's barycenter. Particularly, in the plate-type rotation viscometer, the “shear rate is constant” due to its measurement principle and only the viscosity value can be obtained, expressed in terms of rotational torque.

- Unlike the two methods above, in the vibration viscometer, the oscillators are in reciprocating motion within a liquid. The liquid around the oscillators obtains a “shear rate,” and the accompanying “shear stress” is in turn loaded to the oscillators. By this method, there is neither a barycenter shift nor widespread rotational movement of the liquid, which makes it possible to measure viscosity in the resting state. In addition, the energy possessed by the measuring system of the vibration type is minimum. This means that the energy transferred from the measuring system to a liquid is also minimized. The vibration type is the only method in which no macro movement of the liquid is generated. Thus, I would argue that it is reasonable to term the physical quantity “viscosity × density,” the “static viscosity.” By using the terms “kinetic

viscosity," "viscosity," and "static viscosity," it becomes possible to accurately express the motion or the state of the liquid measured by each viscosity measuring method.

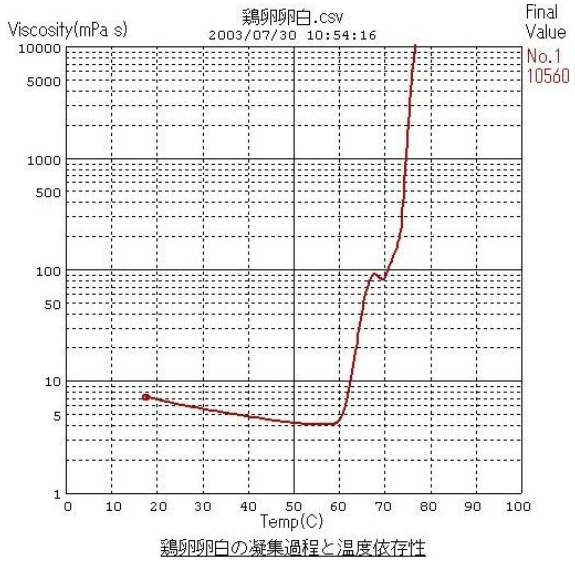
Examples and Future Prospects of Static Viscosity Measurement

The following are actual measurement examples. In some cases, phenomena that once seemed impossible in conventional viscosity measurements, such as cloud point measurements, have been rendered possible, (See Figures 1, 2, 5, & 6).

- Engine oil: Measurement of temperature characteristics of oil from the "static viscosity" of when temperature is changed
- Cloud point measurement: Detection of the cloud point of a nonionic surface-active agent from its "static viscosity" change
- Change from a liquid to a solid: Monitoring the cure process of a protein material (egg albumen) from its "static viscosity" change
- Analysis of constituents of a liquid: Inference of constituent elements by measuring the concentration change of alcohol from the "static viscosity."

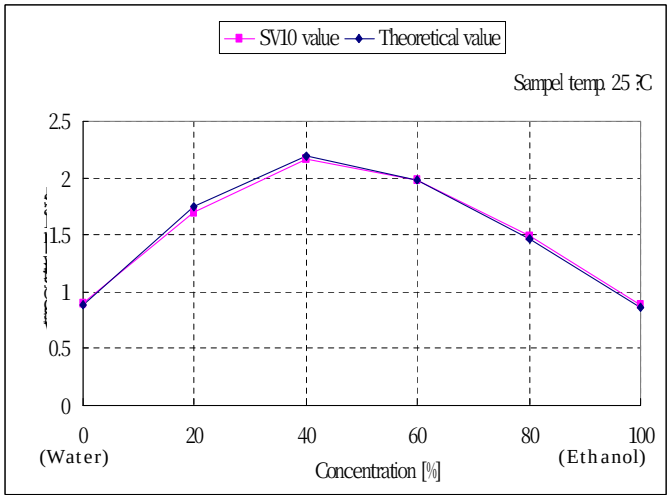
In future measurements of "static viscosity," applications in the following fields may also become possible:

- Evaluating the viscosity of the base material necessary for the measurement of the particle size distribution (evaluation of Brownian motion)
- Inferring the molecular weight of a turbid solution by measuring the viscosity
- Measuring the cure processes and temperature characteristics of functional liquids such as coating materials and inks
- Quantifying the "swallowability" of soft drinks or physical properties of biological objects such as blood viscosity



Coagulation and temperature dependency of chicken egg albumen

Figure 5.



* Theoretical value is corrected for density

Concentration and viscosity of ethanol solution

Figure 6.

Summary

This article provides a brief explanation of the features of a new viscosity measurement method, the tuning-fork vibration viscometer, accompanied by actual measurement examples. The vibration viscometer measures “viscosity × density,” and using water as an example (the temperature coefficient of the density value is as low as 1/100 of the viscosity value) expresses the “viscosity × density” as the “static viscosity.” As a result, it has become possible to easily perform continuous measurements of various viscosity-related physical property changes. Various measuring methods for viscosity and uncertainties of these methods have already been verified and made publicly available as the JCSS standardized methods for viscosity measurement. Based on these experiences, it is expected that there will be more opportunities for precise viscosity measurements in such areas as research & development, production, and quality control in a variety of industries, thereby further contributing to their development.