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Study of Shear Rates Relating to the Measurement of "Static Viscosity"

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Study of shear rates relating to the measurement of "static viscosity"

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ABSTRACT

Making use of a tuning-fork vibro rheometer (viscometer), we measured and studied the viscosity of both Newtonian and non-Newtonian fluids in relation to the parameters of shear rates or the gaps between the sensor plate and the wall surface of cup.

Keywords

Static viscosity {= viscosity x density}, shear rate, tuning fork vibro method, effective value of shear rates, propagation constant of shear rates

1) Introduction

When evaluating the properties of fluids, change in shear rate cannot be ignored. Using a rotational rheometer, let's consider the differences between Newtonian and non-Newtonian fluids in relation to differences in shear rate. For Newtonian fluids, change in shear rate is proportional to shear stress, and its proportionality constant, or the viscosity value, is fixed. On the other hand, for non-Newtonian fluids there is no proportional relationship between changes in shear rate and shear stress, and as a result, the viscosity value as defined as a proportionality constant does not become a fixed value.

From this it can be understood that with a constant shear rate applied to the fluid, if the uniform composition of the fluid, which has a proportional relationship to the change caused by the shear rate, is maintained, the shear stress proportional to shear rate can be obtained, resulting in a constant viscosity value. In other words, it can be said that when the change in composition of the material is in proportion to shear rate for a non-Newtonian fluid, the nonlinearity of the non-Newtonian fluid is attributable to the shear rate generated within the fluid not being proportional to the number of rotations of the rotational viscosity measurement device.

For a non-Newtonian fluid, if it is presumed that there are no changes to the composition other than that proportional to the shear rate, and that the viscosity value points to various forms of nonlinearity, it can be said this means that the shear rate, which is decided by the geometrical shape of the rotational viscosity measurement device, actually differs according to the number of rotations for each type of fluid, or even for identical fluids.

For example, for dilatants such as a suspension of sand and water, potato starch or cornstarch, the sharp change in viscosity demonstrated in relation to shear rate is quite apparent, and the sudden change in viscosity can even be confirmed by the touch of one's hand. As for the change in the value of viscosity for regular non-Newtonian fluids other than dilatants, there is also the fact that, unlike general changes in physical properties caused by stress on materials such as solids or Newtonian fluids, the measurement results are often incongruent with what is felt by touch.

From the above considerations, if the true state of the shear rate, which is inferred to be the main deciding factor of the viscosity of the fluid, can be found, it will probably become a clue in solving questions regarding the behavior of fluids, including non-Newtonian ones. In this study, in order to elucidate the true state of the shear rate, (1) the shear rate is changed by altering the amplitude of the tuning fork vibro viscometer, and (2) by changing the distance between the sensor plates which are used to detect viscosity values and the walls of the container holding the fluid, the case of secondarily changing the shear rate is tested and the influence on the viscosity value from a difference in the shear rate applied to a fluid is examined.

2) Principles and framework of the tuning fork vibro rheometer / Recommendations

- Measurement principle: The history of vibration-type viscometers is long, with publications and research material already available in 1955, more than half a century ago.[*1*2] Such literature introduced the principles of vibration-type devices, explained that the physical quantity amount obtained by measurement was a product of [viscosity x density], and mentioned that the method was also adaptable to non-Newtonian fluids associated with viscoelasticity.

  The tuning fork vibro viscometer uses a method developed from the vibration-type above. In particular, it is a method that uses two oscillators (sensor plates), resonating like a tuning fork, and reduces the reactive force transmitted out of the sensors while heightening the sensitivity. The method also finds the viscosity value from the drive force needed to vibrate the oscillators, under the fixed conditions for displacement (amplitude) called the zero method, using similar constituent parts as an electromagnetic balance.[*3]

- Framework of the device

  The framework of the RV-10000 tuning fork vibro rheometer is presented below in Fig. 1 (external appearance) and Fig. 2 (diagram of the sensor unit). The sensor unit of the tuning fork vibro device consists of an electromagnetic component which generates drive torque, a displacement sensor component which detects the movement of the oscillators and the oscillators themselves which are supported by spring materials with constant elasticity. In fact, these constituent parts are the same as those used in precision electronic balances, and the resolution obtained by dividing 10000 mPa·s – the maximum value of viscosity that can be measured continuously – by the minimum displayable viscosity of d=0.01 mPa·s is equivalent to a precision balance's resolution, which is one scale in a million.

Fig.1　Photograph of RV-10000

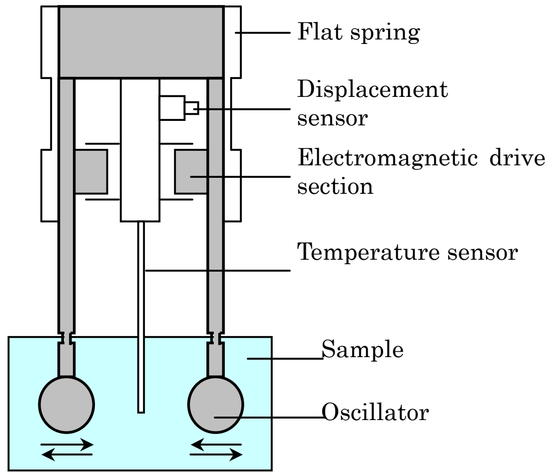

Fig.2　Diagram of measurement unit

- Static viscosity

  With capillary viscometers, [viscosity ÷ density] is measured as kinetic viscosity. With a rotational viscometer (dynamic) viscosity is measured. In contrast to these methods, with vibration-type viscometers [viscosity x density] is obtained, which we defined as “static viscosity”.[*4]

- Effective value of the shear rate

  It is easy to define the shear rate in such a way that when the space between two parallel plates, spreading out to an infinite degree, is filled with a fluid, a constant shear rate is applied between the two plates when one of the plates is moved. However, a viscometer, rheometer, or other viscosity measurement device which faithfully delivers this principle to reality does not yet exist. As the oscillators of the tuning fork vibro method move in a back and forth motion the shear rate keeps on changing over time. Therefore, considering the movement which vibrates as a sine wave, by squaring the amplitude (velocity) of the oscillators at each point in time and adding these values, then calculating the square root of this total, the effective value of the shear rate was defined. The shear rate at each viscosity value measured by the tuning fork vibro rheometer is shown in Fig. 3.

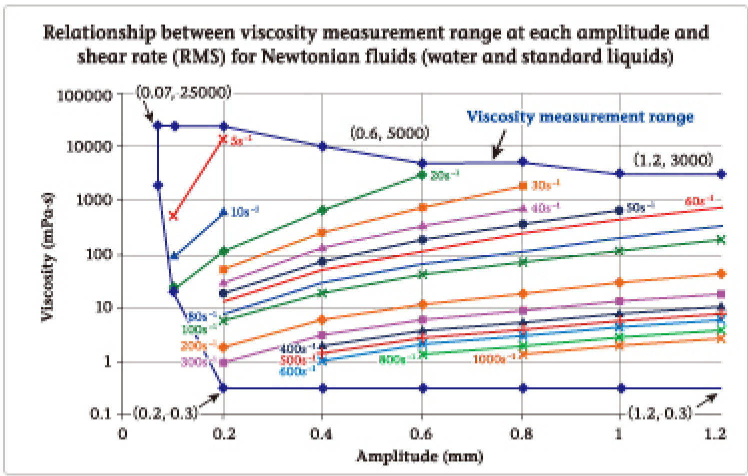

Fig.3 Amplitude of vibrator and viscosity measurement range & shear rate distribution

The border of the graph shows the viscosity measurement range in relation to each amplitude of the oscillators. The curves in the graph express the shear rates at each viscosity of Newtonian fluids. The change in the propagation distance of the shear rate according to the viscosity value even when the same amplitude is applied suggests that shear rate changes according to viscosity value even at the same amplitude, at least for Newtonian fluids.

- Propagation constant of shear rate Fig.4

With the tuning fork vibro method, the oscillators are moved in a liquid of known viscosity and the drive torque required to move them at that time can be measured. The effective value of shear stress is calculated by dividing the shearing force obtained from this drive torque by the area of the wetted surface of the oscillators. Dividing this shear stress by the viscosity value of a known fluid gives the shear rate. Also, the propagation range of the shear rate (stress) with a vibro method can be found with a theoretical formula. It is also possible to infer the propagation range from actual measurements of viscosity using the distance to walls, which forms a boundary condition with the oscillators, as a parameter.

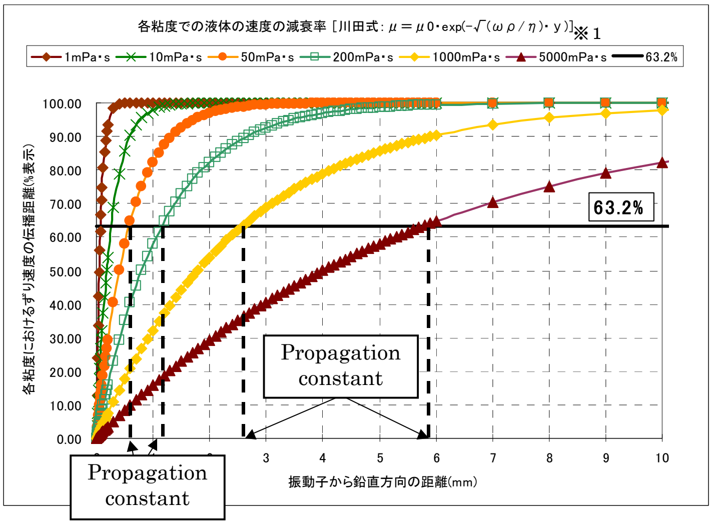

Fig.4 Graph of propagation constant

The propagation distance of the shear rate shall be newly examined. Fig.4 shows propagation ranges for each viscosity value, assuming an infinite receptacle. The points of intercepts of each shear rate propagation curve with the straight horizontal line which intercepts the Y-axis at 0.632 can be measured, with this straight line representing the time constant relative to the maximum propagation distance of the shear rate. This distance is defined as the propagation constant (mm) of the shear rate and shall be used for reviewing the shear rate hereinafter. From this graph it can be seen that even when the viscosity value is as high as 5000mPa·s, the propagation constant of the viscosity is around 6mm and the damping of the shear rate is rapid.

3) Experiment method

Fig. 5: Devices used and format of experiment

Tuning fork vibro rheometer – RV-10000 and its accessories: repeated measurements of viscosity were made using a water circulation jacket, a 13ml glass container and a constant heat water tank widely available for sale to ensure a fixed temperature. The distance between the oscillators and the walls of the container were adjusted using the Y direction mechanism of an XYZ Stage which comes as an accessory of the RV-10000. Also, the amplitude of the oscillators changed in incremental steps of 0.07, 0.1, 0.2, 0.4, 0.6, 0.8, 1.0, and 1.2mm.

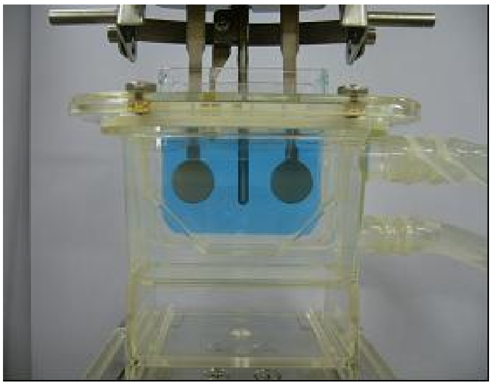

Fig.5 Frontal photograph

Fig.6 Side photograph: thermometer and vibrators in central unit

4) Results of experiment

Rheometer using tuning fork vibro method: The RV-10000 was used altering the amplitude of the oscillators and measuring the viscosity at each different amplitude. The behavior of Newtonian and non-Newtonian fluids was revealed from the measured viscosity values. Data was also collected on the influence of a change in shear rate on a fluid by changing the distance between the oscillators and a container wall and changing the boundary conditions of the shear rate.

- Measurement of change in viscosity when the amplitude of the oscillators and distance between oscillators and wall have been changed

a) Measurement results for purified water Fig.7

Purified water is representative of a Newtonian fluid. Even though the amplitude of the oscillators was altered over 6 steps from 0.2mm (300/s) to 1.2mm (1800/s), if the distance from the wall was kept at a certain level the change in viscosity in relation to the change in amplitude (shear rate) was within the guaranteed repeatability range and an influence could not be seen. However, an increase in viscosity was confirmed the closer the oscillators got to the wall.

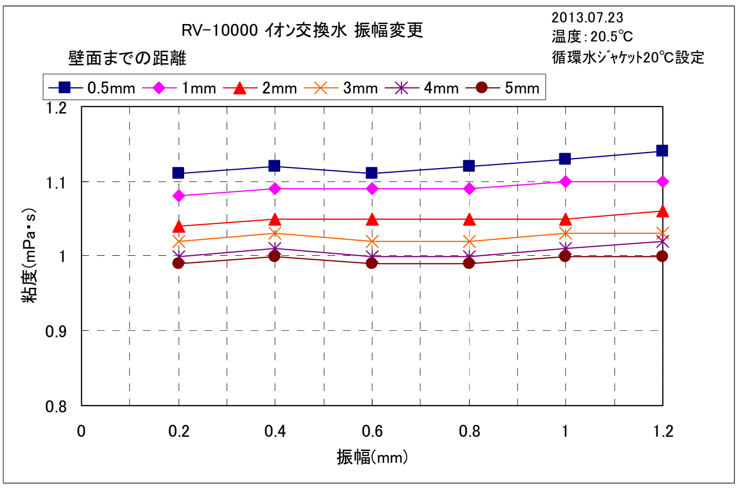

Fig.7 Measurement results for purified water

The sensitivity of the change in viscosity created as the oscillators approach the wall was higher in comparison to the time constant of the shear rate. At 2mm or below, a marked increase in viscosity was confirmed.

b)_Measurement results for a standard viscosity liquid (JS20)

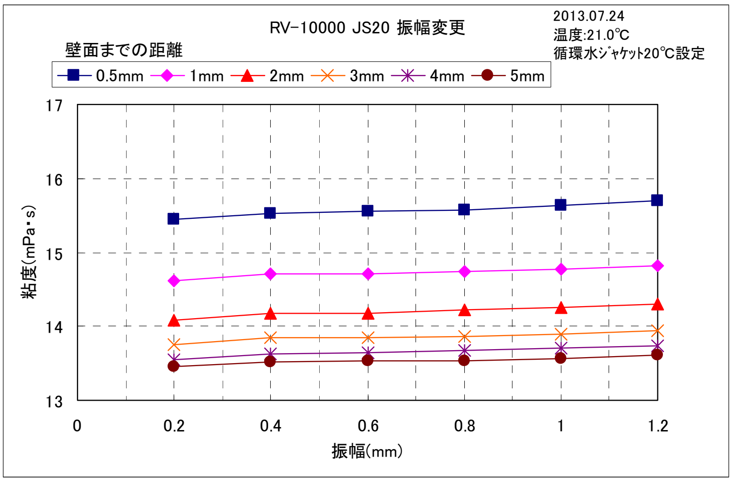

Fig.8 Measurement results for standard viscosity solution JS20

Fig.8 shows the results of measurements of the hydrocarbon standard viscosity liquid JS20. A similar trend was seen to that of purified water, with an increase in viscosity confirmed as the oscillators grew closer to the wall, regardless of amplitude. The viscosity is approximately 10 times that of water, but the rate of increase in viscosity in relation to the closeness of the wall followed a trend close to water.

c) Measurement of fresh cream

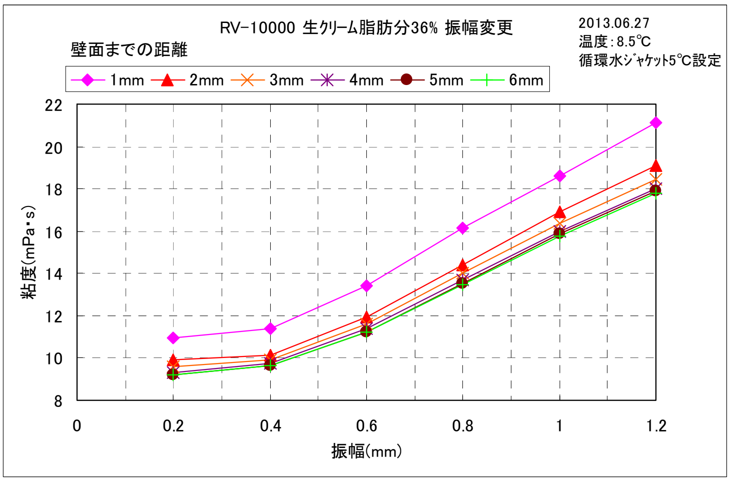

Fig.9 Measurement results for fresh cream

Fig.9 shows the results of measurement of fresh cream. Fresh cream is an uncommon material showing stable dilatant properties. Its viscosity value rises when amplitude rises. It also showed a trend similar to water or JS20 of the viscosity rising as the oscillators got closer to the wall.

5) Conclusions

- With a tuning fork vibro method, by changing the amplitude of the oscillators it is possible to distinguish between Newtonian and non-Newtonian fluids.
- Further, by changing the amplitude of the oscillators it becomes possible to judge a change in viscosity in relation to shear rate for a non-Newtonian fluid.
- When the distance between the oscillators and a wall changed, a change in viscosity was measured. When the distance to the wall became closer than a certain value, a sudden rise in viscosity appears and this phenomenon has been confirmed for both Newtonian and non-Newtonian fluids.

6) Considerations and issues

- By newly introducing and defining the concept of propagation constant of the shear rate, it is now possible to quantify the comparison between theoretical values and actual measurement values with regard to the propagation area of shear rate.
- The influence of the walls of the container on the viscosity value of each fluid becomes noticeable when their distance becomes closer than a certain fixed value. The reach of shear rate propagation was theoretically developed a long time ago as the "damping rate of the velocity of the liquid"*1, but it differs greatly from the actual measurement data obtained by the RV-10000.
- This is the first time actual measurement values have been able to be compared to theoretical values for vibration-type measurement; however, including the scaling, consideration of the influence of the container walls has now become an issue.
- The propagation distance (propagation constant) of the shear rate derived from a theoretical formula is for when the boundary conditions are presumed to be infinite, with the distances for water, viscosity of 10 mPa·s and 50 mPa·s being 0.07mm, 0.25mm and 0.55mm respectively. However, it is now clear from the change in viscosity as measured by the tuning fork vibro method that even when there is a distance of a few millimeters between the oscillators and a wall of the containers, interference exists as a boundary condition and influences a change in the viscosity value.
- In the past, for low viscosity ranges close to water, examples of experiments performing measurements changing the distance between the sensor unit and the walls of the container, while at the same time changing the shear rate to study their correlation, could not be confirmed. One of the reasons for this is the low sensitivity of rotational viscometers which are predominant at present, meaning that (1) the repeatability of measurements in a low viscosity range is particularly poor, and (2) the force applied to the fluid is too strong, creating a change in the constitution of the fluid, meaning they are considered unsuitable for experiments where the distance between the rotor and the circumference is a parameter.
- It was confirmed that the viscosity of water and JS20 were not influenced by shear rate. However, regarding the influence of the distance from a wall, it was clear that if the wall became closer than a few millimeters to the oscillators, similarly to non-Newtonian fluids such as fresh cream there was a strong influence from the wall.
- It is conjectured that the reasons for this are (1) even if the wall is further away than a theoretical limit of reach of the shear rate generated from the oscillators, the shear rate generated from the oscillators and the shear rate reflected from the wall will create an interference with each other, (2) as the oscillators and the wall become close, slipping on the wetted surfaces occurs, and (3) similarly, the influence from interference between the edges of the oscillators and the wall becomes significant.
- The fundamentals of viscosity measurement are shear rate, shear stress and viscosity. Among these, the undetermined element in viscosity measurement is shear rate. Therefore, for the establishment of a basic model relating to viscous properties, it is necessary to continue raising the precision of the theorization of shear rate or attempts at quantification through actual measurements.

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