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Characteristics of Shear-Thinning Fluid Viscosity under Traversal Vibration

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진동장에서의 전단박화 유체 점도의 특성 연구

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Key Words : *Viscosity, shear-thinning, vibration, frequency, shear rate, capillary viscometer*

Abstract

The effect of vibration on the viscosity of a shear-thinning fluid was investigated with a newly designed pressure-scanning capillary viscometer. The viscometer was designed to measure non-Newtonian viscosity continuously over a range of shear rates at a time. Low frequency vibration was applied perpendicularly to the direction of the flow. The effect of the transversal vibration was investigated for both Newtonian fluids and non-Newtonian fluids. The experimental results showed that the vibration had no effect on the viscosity of the Newtonian fluids. However, the vibration caused a significant reduction of the shear-thinning fluid viscosity. The viscosity reduction was strongly dependent on both vibration frequency and shear rate. In addition, the viscosity reduction was affected by the amplitude of vibration, and, the bigger amplitude applied, the more viscosity reduction occurred.

1. Introduction

The shear viscosity of non-Newtonian fluids plays an important role in many industrial applications, including the processing of polymers, foams, pharmaceuticals, and personal care products. Besides the crucial role in the above applications, viscosity is also an omnipresent parameter in liquid state physics. Thus, the fundamental study of the rheological properties has been highly requested in both chemical physics and biophysics.[1]

Recently, there was an interesting research report regarding viscosity with vibration. Deshpande and Barigou [2] investigated the effects of vibration on flow characteristics and reported that flow enhancement was observed for shear-thinning fluid by applying longitudinal vibration to a flowing tube. In addition, the flow enhancement was a function of both vibration frequency and amplitude. A shear-independent fluid such as water showed no difference whether vibration was applied or not. Prior to this report, in fact, there were several research reports on the flow of non-Newtonian fluids in a pipe under the influence of longitudinal oscillation.[3-4] These studies reported that when a non-Newtonian liquid flows through a pipe, the flow rate is increased if the pipe is subjected to a longitudinal oscillation.

Although the effect of vibration on the flow rate has been studied, there is lack of fundamental understanding for rheological property change with vibration. Furthermore, the vibration effect for a shear-thinning fluid should be measured over a range of shear rates since its viscosity varies with shear rates. In the previous experimental results, however, the viscosity measurements with vibration were limited to several shear rates since most existing viscometers produced viscosity measurements one shear rate at a time. In order to measure shear-thinning viscosity with vibration, one needs to repeat the measurement over a range of shear rates by varying either rotating speed or driving pressure for a fixed vibration parameter such as frequency and amplitude, which is a time-consuming process. Furthermore, most viscometer sensors are not suitable to apply vibration because of their inherent characteristics.

Therefore, there has been a need to develop a new method to measure a shear-thinning viscosity over a range of shear rates with vibration. Recently, Shin *et al.* [5-6] introduced two new capillary viscometers that used either a precision load cell or a pressure transducer, respectively. These capillary viscometers enabled the measurement of non-Newtonian viscosity continuously over a range of shear rates at a time. In addition, there was neither difficulty in applying vibration to the instrument nor accuracy decrease due to the vibration. Thus, the present study adopted one of these, the pressure-scanning capillary viscometer [6-7] using the method of data reduction.[5] Thus, the objective of the present study was to investigate the effect of vibration on the viscosity of shear-thinning fluids over a range of shear rates. In order to demonstrate the validity of the pressure-scanning capillary viscometer, the viscosities of water, silicon oil and aqueous polymer solutions were measured without applying vibration and the results were compared with those obtained using a rotating viscometer.

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2. Methods and measurement

Figure 1 is a schematic diagram of the pressure-scanning capillary viscometer (PSCV), which consists of a syringe, vacuum chamber, glass capillary tube, receptacle, precision pressure transducer and computer data acquisition system. The initial volume of the vacuum chamber was 4.363 x 10^4 mm^3. The inside diameter and length of the capillary tube were $_C$ = 1.06 mm and L_C = 200 mm, respectively. The diameter and length of the capillary tube were chosen to ensure that the friction loss in the capillary tube was significantly greater than the loss in the other parts of the system.[6-7] Capillary end effects were accounted for during data reduction analysis by adjusting the values of the length of the capillary tube. The essential feature in a pressure-scanning capillary viscometer is the use of a precision pressure transducer (Validyne DP15TL) to measure the pressure in the vacuum chamber, $P(t)$, every 0.1s with a resolution of 0.25Pa. The instantaneous pressure is recorded in a computer data file through an analog-to-digital data acquisition system (NI DAS-16) with respect to time.

Prior to viscosity measurement, the atmospheric pressure (P_A) and the total volume of the vacuum chamber (V_0) are determined. Typical tests are conducted as follows: The piston in the syringe moves up slowly to lower the pressure of the vacuum chamber so that the inner pressure of the vacuum chamber reaches a preset vacuum pressure or differential pressure (P_i = 8.6 kPa). Once this condition is achieved, the syringe piston is fixed at a position by the stopper throughout the test. At time t = 0, the data acquisition system is enabled and the valve between the vacuum chamber and the capillary is opened, allowing the fluid to flow through the capillary and be collected in the vacuum chamber as driven by the differential pressure. When the differential pressure reaches equilibrium, the test fluid stops flowing.

On the assumption that the product of pressure P(t) and volume V(t) in the vacuum chamber at time t is constant, $P_iV_i = P(t)V(t)$, where subscript i represents the initial state of the experiment and the instantaneous pressure P(t) is recorded in the computer file. The volume of the test fluid filling the vacuum chamber can be calculated as v(t) = V_i-V(t), and the flow rate at time t can be obtained as

$$Q(t) = \frac{dv(t)}{dt} = \frac{dV(t)}{dt} = \frac{d}{dt}\left(\frac{P_iV_i}{P(t)}\right). \qquad (1)$$

On the other hand, the pressure difference through a capillary tube can be expressed as $\Delta P = \{P_A - P(t) - \rho gL\}$ and the corresponding shear stress as $\tau_w(t) = \Delta P(t)D/4L$.

The shear rate at the capillary tube wall is obtained from the classical Weissenberg-Rabinowitsch equation

$$\dot{\gamma}_w(t) = -\left.\frac{dV_z}{dr}\right|_{r=R} = \frac{1}{4}\dot{\gamma}_{aw}\left[3+\frac{d\ln Q}{d\ln \tau_w}\right] \qquad (2)$$

where $\dot{\gamma}_{aw}$ is $4Q/\pi R^3$.

Water, silicone oil (KF-96-20CS, ShinEtsu chemical Co.) and an aqueous solution of commercial polyacrylic acid (Carbopol-934, BF Goodrich Co., Cleveland, OH) were chosen as the test fluids. For comparison purposes, the

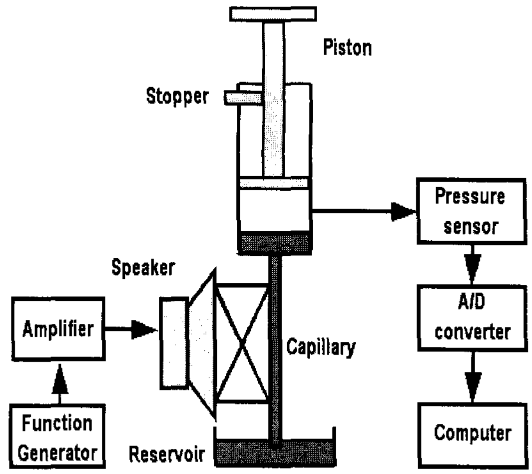

Fig. 1 Schematic of pressure-scanning capillary viscometer (PSCV) system by applying vibration

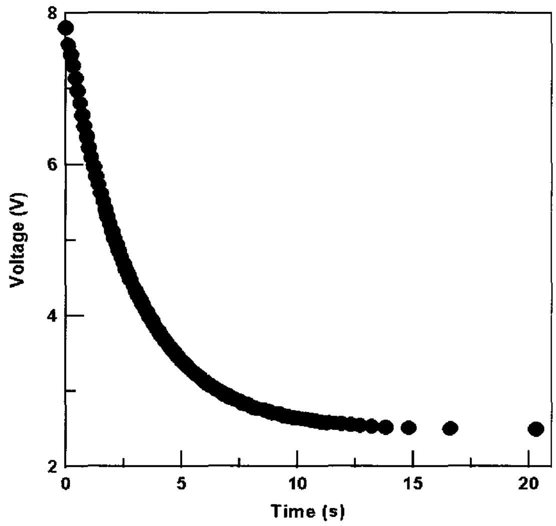

Fig. 2 Pressure differential variations vs. time for water

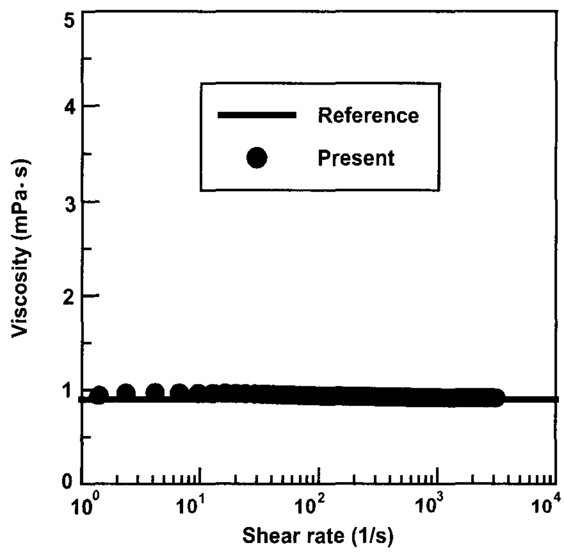

Fig. 3 Viscosity measurement of water at 25°C with PSCV

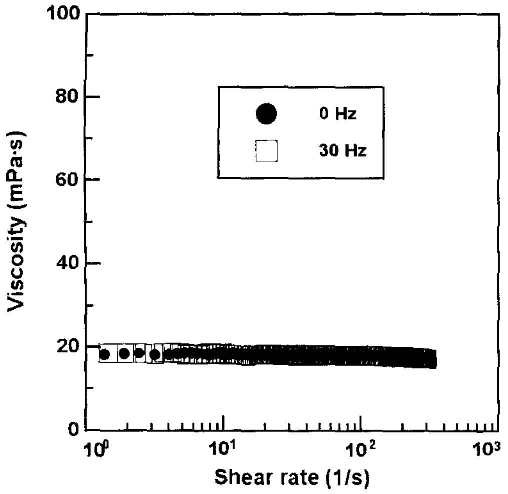

Fig. 4 Viscosity of silicone oil with and without vibrations

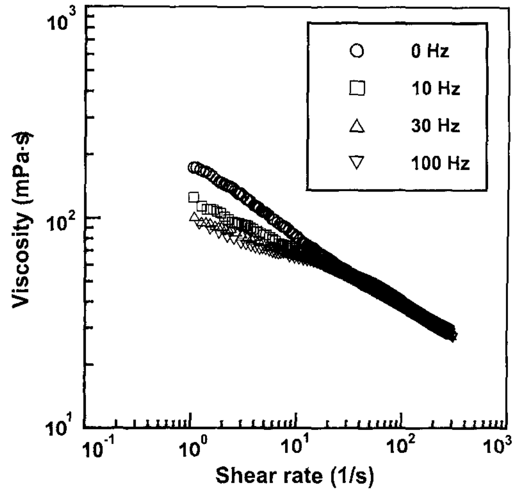

Fig.5 Viscosity vs. shear rate for various frequency vibrations for aqueous polymer solution

viscosity of these fluids was also measured using a rotating viscometer (Physica model UDS-200, Parr Physica, Inc., Glen Allen, VA) at specific temperatures.

3. Results and Discussion

Figure 2 shows the differential pressure variations over time for water. As time passed, the differential pressure between the vacuum chamber and atmosphere decreased since the vacuum chamber was filled with the flowing fluid from the capillary. Typically, it took approximately twenty seconds for water to reach an asymptotic equilibrium. The time to complete a test run should vary depending on the types of liquid and dimensions of the capillary tube. The instantaneous pressure in the chamber was recorded in a computer data file through an analog-to-digital data acquisition system.

Figure 3 shows the viscosity of water at room temperature (25°C) measured with the PSCV. The average value was 0.915 *mPa·s* in a shear rate range between 2 and 3000 s^{-1}. The viscosity of water in the literature is 0.895 *mPa·s*. Compared with this value, the PSCV test results give about 2.2% error across the entire shear rate range.

Figure 4 shows the viscosity of silicone oil at room temperature (25°C) measured with the PSCV. Solid circle symbols indicate the viscosity data measured without applying vibration (0 Hz); open square symbols indicates those measured with a PSCV with applying vibration (f = 30 Hz). For the silicone oil as a Newtonian fluid, its viscosity does not vary whether vibration is applied or not. These results for silicon oil are in good agreement with the previous observations: viscosities of Newtonian fluids are independent of vibration.[2]

Figure 5 shows the viscosity of an aqueous polyacrylic acid solution (Carbopol 1,000wppm) with vibration applied to the capillary tube. As shown in Fig. 5, the shear-thinning viscosity is greatly decreased by vibration over a wide range of shear rates. The viscosity reduction due to vibration was significant at a low shear rates greater than 50 s^{-1}. In addition, as the vibration frequency increases, the

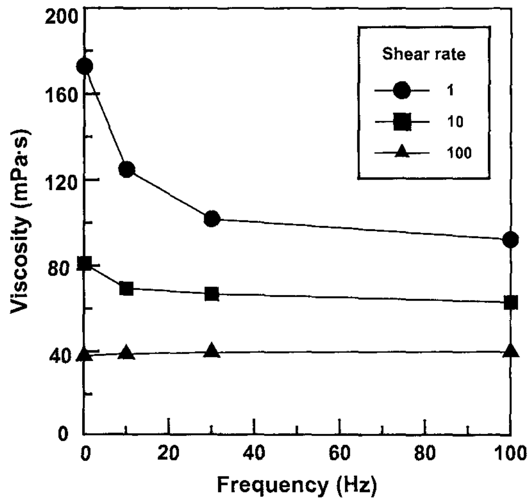

Fig.6 Viscosity vs. frequency for several shear rates for aqueous polymer solution

viscosity of the shear-thinning fluid gradually decreases and seems to reach an asymptote. It is important to note that the vibration should be characterized by both frequency and amplitude. When the vibration frequency varies, the amplitude of vibration should be constant. In Fig.5, the amplitude was fixed as Δ = 0.3 mm while the frequency varies. Figure 6 shows the viscosity reduction with varying vibration frequency for the fixed amplitude (Δ = 0.3 mm).

For low shear rate, the shear-thinning viscosity is greatly reduced by vibration (i.e., from 0.173 *Pa·s* to 0.095 *Pa·s*) and approaches an asymptote value as the frequency increases. The viscosity at a relatively high shear rate (SR = 100 s^{-1}) does not show any decrease with vibration frequency, which seems to be an infinite shear rate viscosity.

In Figures 7 and 8, the effect of the amplitude of vibration on the shear-thinning viscosity was delineated for a fixed frequency (f = 30 *Hz*). Figure 8 shows the viscosity versus shear rate for the aqueous Carbopol solution

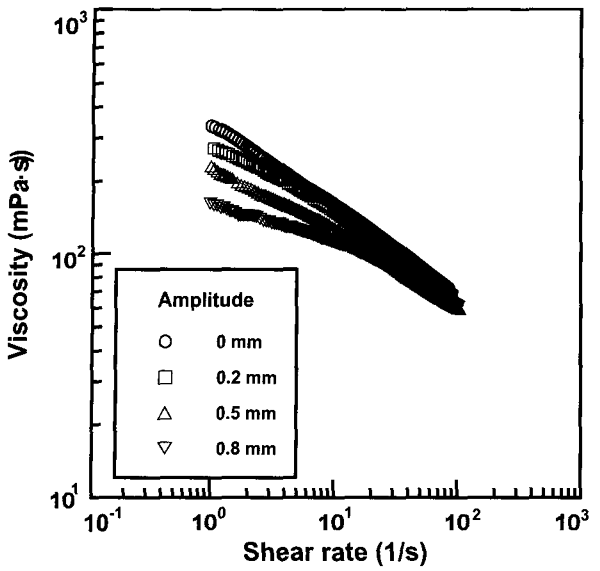

Fig. 7 Viscosity vs. shear rate for various amplitudes for aqueous polymer solution

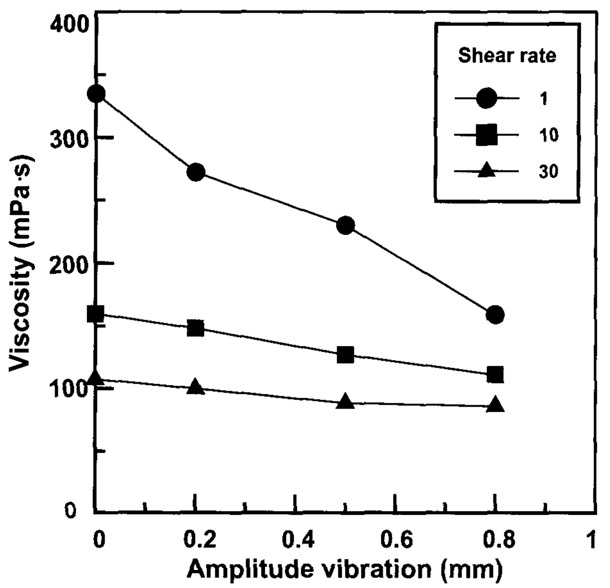

Fig. 8 Viscosity vs. amplitude for several shear rates for aqueous polymer solution

(1,000wppm) with varying amplitude of the vibration. Similar to the effect of the frequency of vibration, the viscosity of the shear-thinning fluid is greatly affected by the amplitude of vibration over a wide range of shear rates. As the vibration amplitude increases, the viscosity decreases. The viscosity reduction shows larger value in a low shear rate region than in a high shear rate region.

Figure 8 shows the viscosity versus amplitude of vibration for several shear rates. As shown in Fig. 8, the viscosity decreases linearly with the amplitude of vibration and is much larger at a low shear rate (SR = 1 s^{-1}) than at a high shear rate (SR = 30 s^{-1}). Further reduction of viscosity is expected when larger amplitude of vibration is applied to the shear-thinning fluid flow.

4. Conclusions

The present study investigated the effect of the transversal vibration on the viscosity of shear-thinning fluids using a newly designed pressure-scanning capillary viscometer. Both frequency and amplitude of vibration were found to be the main parameter causing viscosity reduction for the shear-thinning fluid. Viscosity reduction due to vibration was greater at a low shear rate than at a high shear rate. The shear-thinning viscosity decreased exponentially with increasing frequency and approached an asymptote. Beyond a critical frequency, further viscosity reduction would not be expected. In addition, the viscosity reduction was linearly increased by increasing the amplitude of vibration and did not show an asymptote value, implying that the larger the amplitude is applied, the more viscosity reduction occurs. Conclusively, the present study confirmed that the transversal vibration caused no viscosity reduction for Newtonian fluid but a significant viscosity reduction for the shear-thinning fluid, which was a function of not only the amplitude but also the frequency of vibration.

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