Blood Viscosity Measurements Using a Pressure-Scanning Capillary Viscometer

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A previously designed capillary viscometer with measuring differential pressure was modified to measure the viscosity of non-Newtonian fluids including unadulterated blood continuously over numerous shear rates in a single measurement. Because of unavoidable experimental noise and a limited number of data, the previous capillary viscometer experienced an inaccuracy and could not directly determine a viscosity without an iterative calculation. However, in the present measurement there are numerous data available near the point of interest so that the numeric value of the derivative, $d(\ln Q)/d(\ln \tau_w)$, is no longer sensitive to the method of differentiation. In addition, relatively low and wide shear rate viscosity measurements were possible because of the present precision pressure-scanning method with respect to time. For aqueous polymer solutions, excellent agreement was found between the results from the pressure-scanning capillary viscometer and those from a commercially available rotating viscometer. In addition, the pressure-scanning capillary viscometer measured the viscosity of unadulterated whole blood without adding any anticoagulants.

Key Words: Blood Viscosity, Non-Newtonian Fluids, Shear Rates, Pressure, Capillary Viscometer.

Nomenclature

L : Length (m)
P : Pressure (Pa)
Q : Volume flow rate (m^3/s)
t : Time (s)
V : Volume (m^3)
v : Velocity (m/s)

Greek Symbols

ρ : Density (kg/m^3)
ϕ : Diameter (m)
$\dot{\gamma}$: Shear rate (s^{-1})
η : Non-Newtonian viscosity (Pa·s)
τ : Shear stress (Pa)

Subscripts

A : Atomospheric condition
C : Capillary tube
h : Head
i : Initial
w : Wall

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1. Introduction

It is commonly known that blood viscosity plays a critical role in determining the work of the heart that is exerted on the vascular system (Dintenfass, 1969; Kensy and Cho, 1992; Fossum et al., 1997). Since whole blood viscosity directly correlates to the work of the heart, it is of importance to measure whole blood viscosity like blood pressure. Although there are many methods and instruments to measure viscosity, most current technology, while useful in a research setting, is not optimal for day-to-day clinical use (Chandler and Schmer, 1986). Furthermore, most exis-

ting viscometers produce viscosity measurements for one shear rate at a time. In order to measure blood viscosity that is shear-dependent, one needs to repeat the measurement over a range of shear rates by varying either rotating speed or driving pressure, which is a time-consuming process.

At present, due to the time-consuming process, most blood viscosity measurements require anti-coagulants in blood to prevent blood coagulation, that may increase or decrease blood viscosity depending on the types of anticoagulants (Singh and Coulter, 1973; Reinhart et al., 1990) Hence, these methods are not suited for viscosity measurements of unadulterated blood since they should be completed within a few minutes. Furthermore, due to the limited number of data and unavoidable experimental noise, most of the existing methods that process capillary viscometry data have difficulty in direct calculation of viscosity without iterative procedures.

In fact, the direct calculation of viscosity requires obtaining a differentiation of $\ln Q$ with respect to $\ln \tau_w$, which is a key parameter in the Weissenberg-Rabinowitsch equation (Shin and Keum, 2002a). However, it has been shown that the derivative value with limited data was very inaccurate and sensitive to the differentiation method performed (Macosko, 1993; Nguyen et al., 1999). Therefore, there is a need to develop a viscometer that can complete the measurement in a few minutes and produce a number of data near the point of interest for stable and accurate differentiation of $d(\ln Q)/d(\ln \tau_w)$.

Ogawa et al. (1991) introduced a blood viscometer with a vacuum glass tube and needle to measure the viscosity of blood and non-Newtonian fluids over a range of shear rates. However, viscosity was measured in a high shear rate region ($2{,}000 \sim 22{,}000\ s^{-1}$) due to the apparatus characteristics. Hence, their results did not show a shear-thinning characteristic of blood viscosity. Furthermore, this apparatus was not able to produce a great amount of data, which caused inaccuracy in obtaining the differentiation of $\ln Q$ against $\ln \tau_w$ in the Weissenberg-Rabinowitsch equation. Thus, they adopted a non-Newtonian viscosity model and calculated the viscosity with an iterative procedure.

Shin et al. (2002a, 2002b) introduced a new mass-detecting capillary viscometer that uses a precision balance to measure the viscosity of non-Newtonian fluids and human blood. This mass-detecting capillary viscometer produced lots of viscosity data over wide range of shear rates, which leads to a stable and accurate differentiation of $d(\ln Q)/d(\ln \tau_w)$.

The objective of the present study is to develop a pressure-scanning capillary viscometer that can accurately measure unadulterated blood viscosity without an iterative calculation. The present study modified the vacuum glass tube viscometer (Ogawa et al., 1991) by adopting the method of directly determining shear rate and viscosity used in the mass-detecting capillary viscometer (Shin and Keum, 2002a). The flow rate and pressure-drop measurements that are usually required in capillary-tube viscometry are replaced with a single measurement of pressure variation in the vacuum tube due to the flow through the capillary tube with respect to time, $P(t)$. From this measurement, the viscosity and shear rate were directly calculated without iterative processes.

In order to demonstrate the validity of this new pressure-scanning capillary viscometer, the viscosity data for test fluids were compared to data obtained from a rotating viscometer and its reference value.

2. Materials and Methods

Figure 1 is a schematic diagram of the modified pressure-scanning capillary viscometer (PSCV), which consists of a syringe, vacuum chamber, glass capillary tube, receptacle, pressure transducer and computer data acquisition system. The initial volume of the vacuum chamber was $2.5 \times 10^5\ mm^3$. The inside diameter and length of the capillary tube were $\phi_C = 1.93$ 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 (Shin et al., 2002a). Capillary end effects

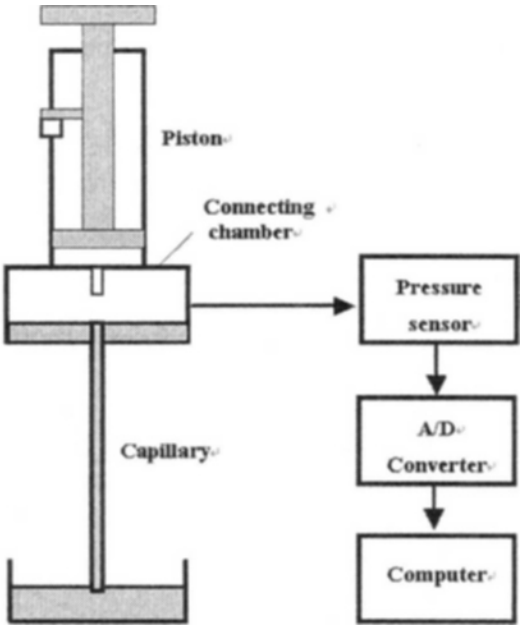

Fig. 1 Schematic diagram of a pressure-scanning capillary viscometer system

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 0.1 s with a resolution of 0.25 Pa. The pressure transducer has a fast dynamic frequency response (1 kHz) to trace the changes in chamber pressures. Furthermore, in the calibration of the pressure transducer, pressure versus voltage curve shows an excellent linearity in the present pressure measurement range, which enables to directly convert the voltage to an actual pressure. 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. With the acquired data, the viscosity of a fluid is determined through a simple data processing program (MS-excel®).

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 suck the air from the vacuum chamber so that the inner pressure of the vacuum chamber reaches a preset differential pressure (ΔP_i=8.6 kPa). Once this condition is achieved, the syringe piston is fixed at a position by the stopper through-out 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 with a pressure head (ΔP_h=1.95 kPa), the test fluid stops flowing.

A detailed description to derive the viscosity relation can be found in a previous study (Ogawa et al., 1991). A brief description is as follows: 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 $v(t)=Vi-V(t)$ and the flow rate at time t can be obtained as

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

On the other hand, the pressure difference through a capillary tube can be expressed as $\Delta P=\{P_A-P(t)-\rho g^L\}$ 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 (Bird et al., 1987)

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

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

Water and aqueous solutions of commercial polyacrylamide (Separan AP-273, Dow Chem. Co.) and polyacrylic acid (Carbopol-934, BF Goodrich Co.) were chosen as the test fluids. For comparison purposes, the viscosity of these fluids was also measured using a rotating viscometer (Physica model UDS-200, Parr Physica, Inc.) 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 thirty 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.

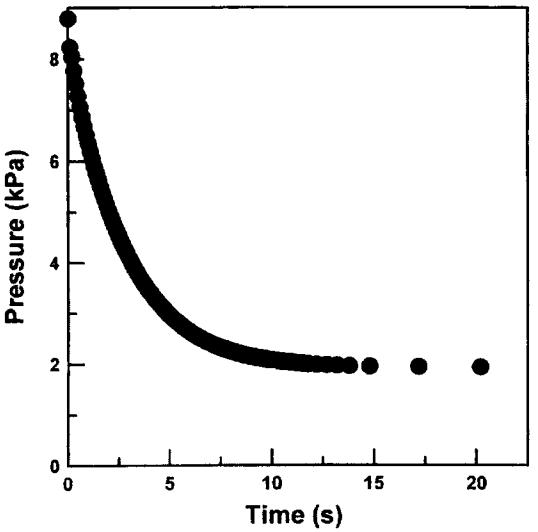

Fig. 2 Pressure variations vs. time for water

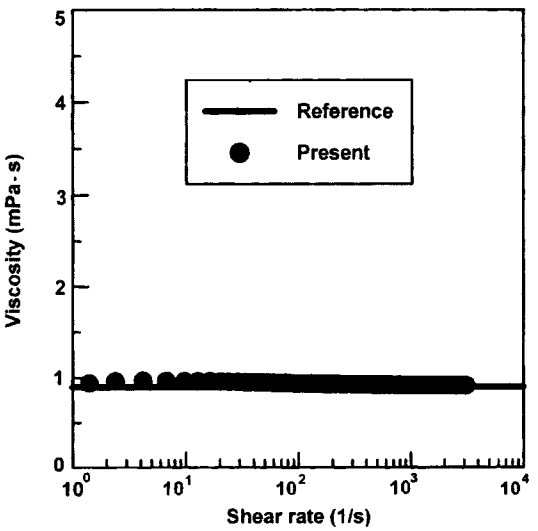

Fig. 3 Viscosity measurement for water at 20℃ with a PSCV

Figure 3 shows the viscosity of water at room temperature (20℃) 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 (Lide, 1994) is 0.895 mPa·s. Compared with this value, the PSCV test results give about 2.2% standard deviation across the entire shear rate range.

Figure 4 shows a typical log-log plot of volume flow rate (Q) against pressure drop (ΔP) for the aqueous Separan solution (1,000 wppm) at room temperature. The typical number of data points in a pressure-scanning capillary viscometer is about one thousand over a range of shear rates. Therefore, even if there is unavoidable noise in the data, the value of the numeric derivative, $d(\ln Q)/d(\ln P)$, with a number of data at a point of interest can be very stable regardless of the means of differentiation. This rigorous approach can still be taken to obtain a viscosity versus shear rate relationship for any fluid without adopting a specific non-Newtonian viscosity model.

Figures 5 and 6 show the viscosity results

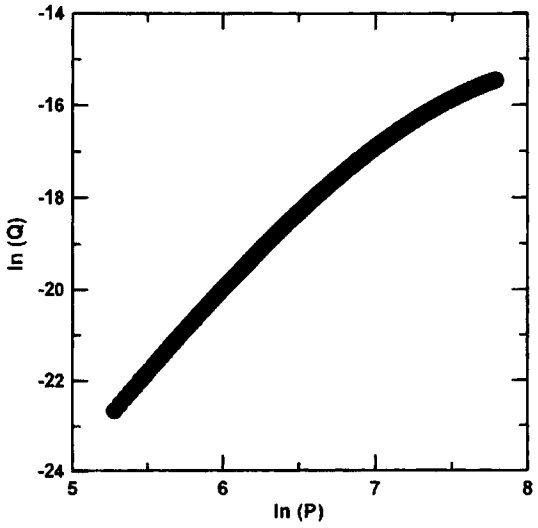

Fig. 4 Logarithmic volume flow rate versus logarithmic pressure drop occurring through the capillary tube

obtained with the aqueous Separan and Carbopol solutions at room temperature, respectively. Open circle symbols indicate the viscosity data measured with a rotating viscometer ; solid circle symbols indicate those measured with PSCV. The

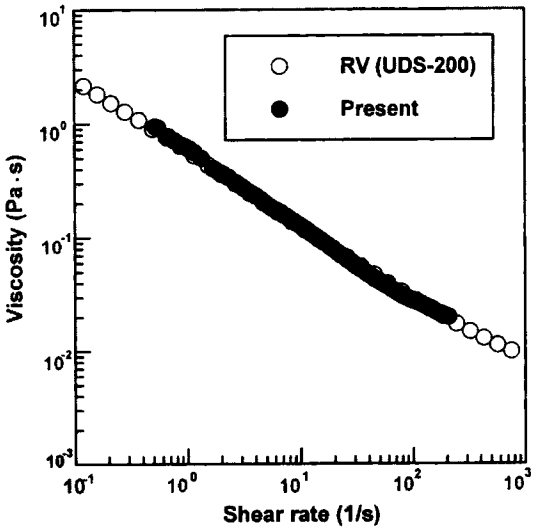

Fig. 5 Viscosity measurement (log-log scale) for aqueous polyacrilamide solution (Separan 1,000 wppm) with a rotating viscometer and PSCV

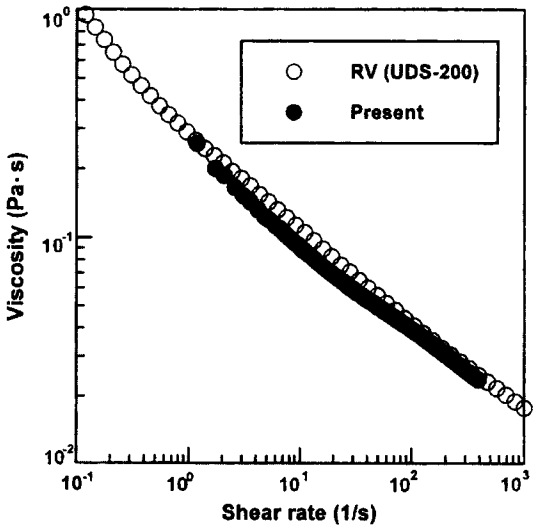

Fig. 6 Viscosity measurement (log-log scale) for aqueous polyacrilic acid solution (Carbopol 1,000 wppm) with a rotating viscometer and PSCV

PSCV results show excellent agreement (less than 2.5%) with those from the commercial viscometer over a range of shear rate ($10^0 \sim 10^3\ s^{-1}$).

Figsure 7 and 8 show test results obtained with unadulterated human blood without introducing anticoagulants or EDTA with PSCV. The present study tested blood viscosity with a blood donor as a proof of principle. Figure 7 shows the pressure variation over time for unadulterated blood. The

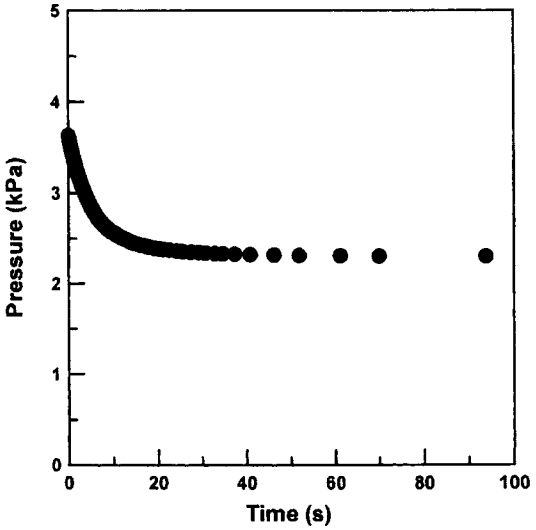

Fig. 7 Pressure variations along time for unadulterated blood

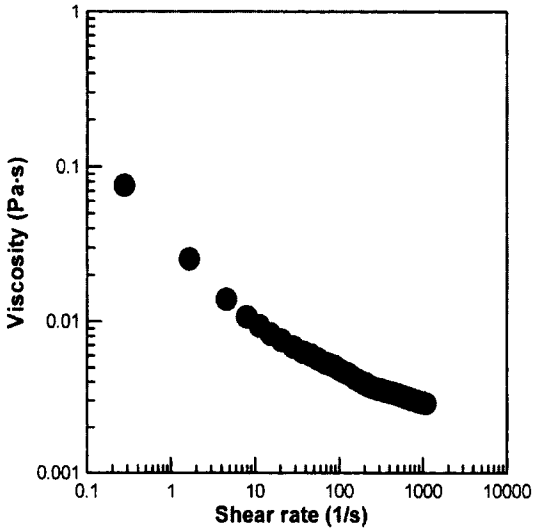

Fig. 8 Viscosity of unadulterated blood with a PSCV

trends of the pressure variations are very similar to those for water.

It is important to note that the test should be completed within 2 minutes. If not, blood may begin to clot. In this measurement, one test run took less than 2 minutes. Figure 8 shows the viscosity results of unadulterated human blood at 37℃ for a healthy male donor. The blood viscosity was measured over a range of shear rate from 0.1 through 1000. In this low to moderate shear rate region, blood viscosity shows a strong shear-thinning viscosity that cannot be observed in a high shear rate region (Ogawa et al., 1991). In fact, as Eckmann et al. (2000) reported, blood viscosity is a strong function of temperature, shear rate, hematocrit, etc. The variation of blood viscosity depending on the sample can be detected with the present viscometer without adding any anti-coagulants.

4. Conclusions

This study developed a new method of measuring unadulterated blood viscosity without anticoagulants over a range of continuous shear rates from high to low ranges (as low as 1 s^{-1}). The feasibility and accuracy of this new viscosity measurement technique have been demonstrated for distilled water and an aqueous polymer solution by comparing the results against an established viscosity measurement technique with a rotating viscometer. Among the advantages of this new viscometer are simplicity (i.e., ease of operation and no moving parts), quick measurement and the ability to make accurate measurements over a relatively broad shear rate range without using anticoagulants.

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