Measurements of Blood Viscosity Using a Pressure-Scanning Slit Viscometer

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A newly designed pressure-scanning slit viscometer is developed to combine an optical device without refraction while measuring blood viscosity over a range of shear rates. The capillary tube in a previously designed capillary viscometer was replaced with a transparent slit, which is affordable to mount optical measurement of flowing blood cells. Using a pressure transducer, we measured the change of pressure in a collecting chamber with respect to the time, $p(t)$, from which the viscosity and shear rate were mathematically calculated. For water, standard oil and whole blood, excellent agreement was found between the results from the pressure-scanning slit viscometer and those from a commercially available rotating viscometer. This new viscometer overcomes the drawbacks of the previously designed capillary viscometer in the measuring whole blood viscosity. First, the pressure-scanning slit viscometer can combine an optical instrument such as a microscope. Second, this design is low cost and simple (i.e., ease of operation, no moving parts, and disposable).

Key Words : Blood, Viscosity, Pressure, Slit, Viscometer

Nomenclature

h : Half slit gap (mm)
L : Slit length (m)
P : Pressure (Pa)
Q : Flow rate (m^3/s)
t : Time (s)
V : Volume (m^3)
v : Voltage (V)
w : Slit width (mm)

Greek Symbols

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

Subscripts

A : Atmospheric condition
h : Head
i : Initial
w : Wall

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1. Introduction

It is commonly known that blood viscosity plays a critical factor with regard to cardiovascular diseases including atherosclerosis and hypertension (Dintenfass, 1969; Fossum et al., 1997). Since whole blood viscosity directly correlates to the work of the heart, it is important to measure whole blood viscosity in the same manner as 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). In fact, most existing viscometers are designed for laboratories and industries so that viscosity measurement requires a labor-intensive and time-consuming process. Furthermore, recent technology development tends to

combine optical measuring function with viscometry. However, the previous designed capillary viscometers cannot be extended to combine with optical measurement. The previous researches are briefly reviewed in the following.

At present, due to the time-consuming process, most blood viscosity measurements require anticoagulants in the blood to prevent coagulation, which result in including the effects of anticoagulants that may increase or decrease blood viscosity depending on the type 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 directly calculating viscosity without iterative procedures (Macosko, 1993).

Kim et al.(2000) introduced a scanning-capillary-tube viscometer that uses a charge-coupled-device sensor array to measure the viscosity of bovine blood and whole blood using a CCD sensor array. This scanning capillary tube viscometer can produce viscosity data in a low shear range by extending the shear rate range as low as 1 s^{-1} for human blood at body temperature. This method, however, requires a non-transparent test fluid due to its optic measurement, which is not applicable to transparent fluids such as serum and plasma.

Meanwhile, Shin and Keum (2002a, b) introduced a new mass-detecting capillary viscometer that uses a load cell to measure the viscosity of Newtonian and non-Newtonian fluid. This mass-detecting capillary viscometer can produce viscosity data in a low shear range by extending the shear rate range as low as 1 s^{-1} for water within a minute. In addition, Shin et al. (2002c) developed a new pressure-scanning capillary viscometer that uses a pressure-transducer to measure the viscosity of non-Newtonian fluids including blood.

Even though the above described viscometers were designed to be used in a clinical setting, these viscometers, however, are not suitable to attach optical measurements such as microscope or ektacytometry due to its circular shape of the cross section. Thus, the objective of the present study is to develop a slit viscometer which can be combined with optical systems. In the present study, the capillary tube was replaced by a transparent slit. Throughout the development of the present viscometer, an emphasis has been placed on the simplicity of design that would be multi-functional and quick-and-easy to operate.

In order to demonstrate the validity of this new pressure-scanning slit viscometer, the viscosity data was compared with data obtained from a rotating viscometer with high resolutions (Physica UDS-200, Parr Physica, Inc., Glen Allen, VA). Also, the accuracy of the new instrument was demonstrated by measuring the viscosity of water and comparing the results with its reference value.

2. Materials and Methods

Figure 1 shows a schematic diagram of the modified pressure-scanning slit viscometer (PSSV). Details of the viscometer consist of a vacuum chamber, connecting needle, collecting chamber, slit, receptacle, pressure transducer and a computer data acquisition system. With vacuum suction, the 5 blood sample in the receptacle flows through the slit made of glass. The glass slit integrated with a collecting chamber is designed to be disposable. The half gap of the slit was $h=$ 0.40 mm. The width and length of the slit were

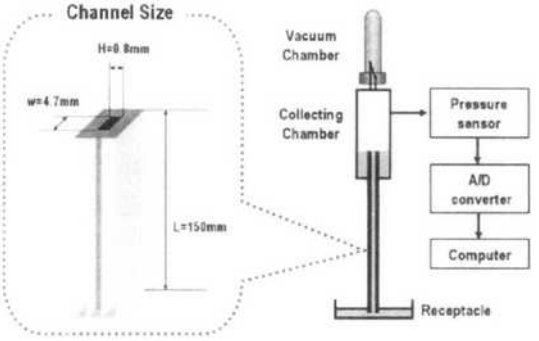

Fig. 1 Schematic diagram of a pressure-scanning slit viscometry

w=4.7 mm and L=150 mm, respectively. The gap and length of the slit were chosen to ensure that the friction loss in the slit was significantly greater than the loss in other parts of the system (Shin et al, 2002a ; Kim et al., 2000).

The slit gap was carefully chosen to minimize the Fahraeus-Lindqvist effect (Fahraeus and Lindqvist, 1931). The Fahraeus-Lindqvist effect is a phenomenon that in tube flow, red blood cells (RBC) tends to migrate toward the center of the tube. The plasma-rich zone next to the tube wall, although very thin, has an important effect on blood viscosity measurement, which results in viscosity decreases with decreasing tube diameter. The wall effect was found to be neglected when the tube diameter is bigger than approximately 800 μm (Haynes, 1960). Even though the Fahraeus-Lindqvist effect in a slit has not been reported in literature, the slit gap in the present study was 800 μm according to the Haynes' report (1960).

The essential feature in the pressure-scanning slit viscometer is the use of a precision pressure transducer (Druck, PMP-4170) to measure the pressure in the vacuum chamber, $P(t)$, every 0.05 s with a resolution of 0.6 Pa. The pressure transducer has a fast dynamic frequency response (2 kHz) to trace the changes in the chamber pressure. Furthermore, in the calibration of the pressure transducer, the pressure versus voltage curve shows excellent linearity in the present pressure measurement range, which enables to directly convert 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 the viscosity measurements, 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 extract the air from the vacuum chamber so that the inner pressure of the vacuum chamber reaches a preset differential pressure (ΔP_i=6.5 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 to be collected in the vacuum chamber as driven by the differential pressure. When the differential pressure reaches equilibrium with a pressure head (ΔP_h=1.46 kPa), the test fluid stops flowing.

A detailed description to derive the viscosity relation can be found in a previous study (Shin et al., 2002c). A brief description is as follows: On the assumption that the air in the vacuum chamber is an ideal gas, it was found 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

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

where the subscript i indicates initial condition.

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 $\tau_w(t)=\Delta P(t)\,h/\{L(1+2h/W)\}$. The shear rate at the capillary tube wall is obtained from the classical Weissenberg-Rabinowitsch equation (Bird et al., 1987)

$$\dot{\gamma}_w(t)=\frac{1}{3}\dot{\gamma}_a\left[2+\frac{d\ln Q}{d\ln \tau_w}\right] \quad (2)$$

where apparent shear rate, $\dot{\gamma}_a$ is $6Q/(\pi h^2)$ and the subscript w indicates wall. Then, the shear rate and the shear stress are obtained at an arbitrary time. Thus, the viscosity can be determined as $\eta=\tau_w/\dot{\gamma}_w$.

Water and an aqueous solution of commercial polyacrylamide (Separan AP-273, Dow Chem. 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 fluid flowing through the slit. 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 slit.

Figure 3 shows the viscosity of water at room temperature (24.8±0.1℃) measured with the PSSV. The average value was 0.924 mPa·s in a shear rate range between 0.1 and 1000 s^{-1}. The viscosity of water in the literature (Lide, 1994) is 0.915 mPa·s. Compared with this value, the PSSV test results show about a 0.5% standard deviation across the entire shear rate range.

Figure 4 shows the viscosity results obtained with a standard oil (Brookfield 010203) at room temperature (25±0.1℃). Open circle symbols indicate the viscosity data measured with a rotating viscometer; solid circle symbols indicate those measured with a PSSV. The average value measured by the PSSV was 4.87 mPa·s in a shear rate range between 0.2 and 4000 s^{-1}, which is in excellent agreement (less than 2.5%) with the given data (4.8 mPa·s at 25℃) from the supplier. The viscosity of the standard oil measured by the rotating viscometer (Physica UDS-200) shows

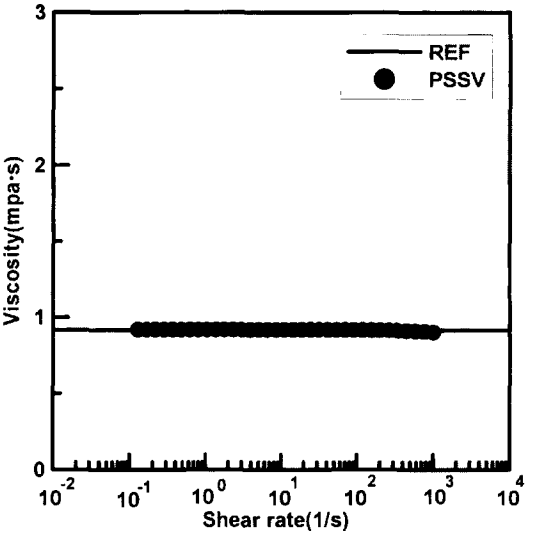

Fig. 3 Viscosity measurement for water at 24.8℃ with a PSSV

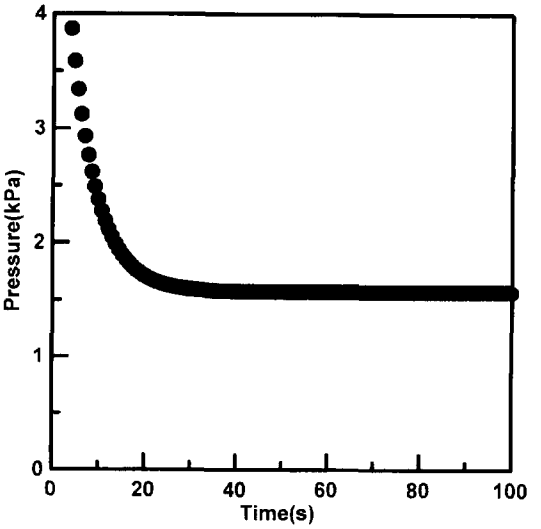

Fig. 2 Pressure variations vs. time for water

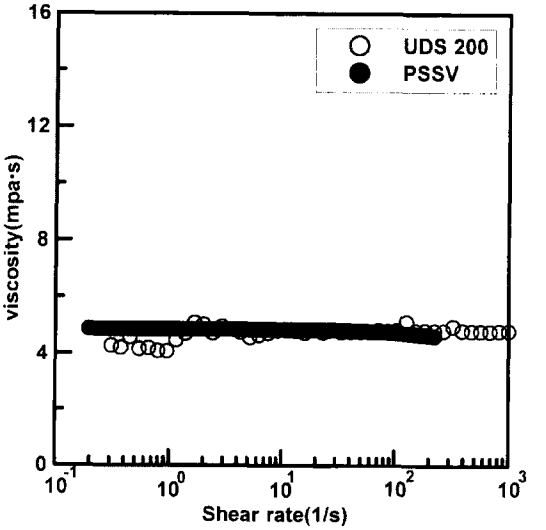

Fig. 4 Viscosity measurement for standard oil with a rotating viscometer and PSSV

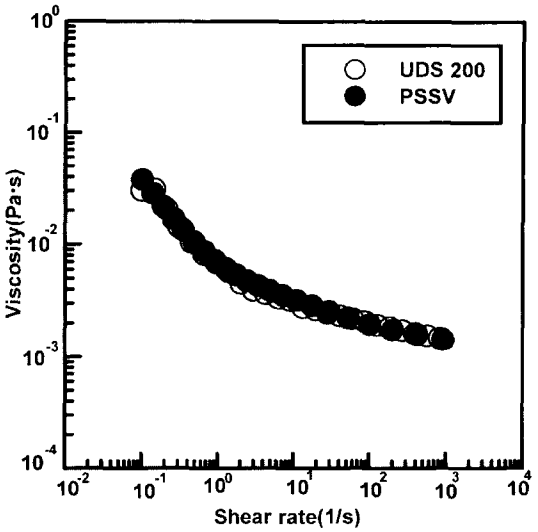

Fig. 5 Viscosity measurement (log-log scale) for aqueous polyacrylamide solution (Separan 50 wppm) with a rotating viscometer and PSSV

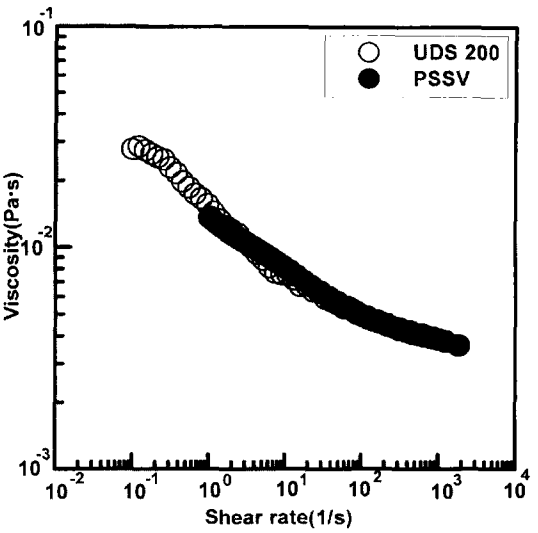

Fig. 6 Viscosity of whole blood with PSSV

accurate results over the range of shear rate except for the low shear rate region, in which the torque sensor mounted in the rotating viscometer cannot accurately detect the applied small torque.

Figure 5 shows the viscosity results obtained with the aqueous polyacrylamide (Separan™, 50 wppm) solutions at room temperature, respectively. Open circle symbols indicate the viscosity data measured with a rotating viscometer ; solid circle symbols indicate those measured with a PSSV. The PSSV results show excellent agreement (less than 4.8%) with those from the commercial viscometer over a range of shear rates ($10^{-1} \sim 10^{3}\ s^{-1}$).

Figures 6 shows test results obtained with human blood with the PSSV and the rotating viscometer. The present study tested blood viscosity with a blood donor as a proof of principle. In our measurement, one test run took less than 30 s. As shown in Fig. 6, the blood viscosity was measured over a range of shear rate from 1 through 1000. Open circle symbols indicate the viscosity data measured with a rotating viscometer ; solid circle symbols indicate those measured with a PSSV. The PSSV results show excellent agreement (less than 4.8% of error) with those from the commercial viscometer over a range of shear rates ($10^{0} \sim 10^{3}\ s^{-1}$). In this low to moderate shear rate region, the blood viscosity shows a strong shear-thinning viscosity that cannot be observed in a high shear rate region (Ogawa et al., 1991).

4. Conclusion

This study developed a new method of measuring whole blood viscosity with a slit over a range of continuous shear rates from a high to low range (as low as $0.1\ s^{-1}$). The feasibility and accuracy of this new viscosity measurement technique have been demonstrated for distilled water, a standard oil 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 the applicability of an optical measurement, quick and easy to handle, and the reliable accuracy over a relatively broad shear rate range.

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