Microfluidics and Rheology of Carbon Black Dilute Suspensions: Modeling, Measurement, and Applications

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ABSTRACT

Microfluidics and rheology are critical in designing microfluidic systems. A study of the slip flow and rheological properties of suspension fluids becomes more challenging at microscale levels. In this work, a customized microslit rheometer has been developed and used to test carbon black suspensions using micrometer-sized channel gaps (25 μm and 100 μm). A reduced viscosity of the suspension fluid due to wall slip was found in the 25-μm-gap channel. Rheological models for the microslit rheometer were derived using no-slip and slip boundary conditions to calculate the viscosity of the suspension fluid at the microscale level. By analyzing the viscosity data using the developed rheological models, we can determine the values of the slip parameter, known as slip length (β).

Keywords: microfluidics, rheology, slip flow, and carbon black suspension

1 INTRODUCTION

Microfluidics deals with transport phenomena of fluid flows in fluid-based systems at microscopic length scales, typically 1 to 100 μm. In recent decades, microfluidics has become a popular and promising research topic due to the development of microelectromechanical systems (MEMS) technology and biochemical lab-on-a-chip devices. Microfluidic devices provide benefits over macroscopic devices such as lower material consumption, faster response/reaction time, better portability, and the possibly new functionality. The understanding of the flow behavior in microchannels is essential in designing, analyzing, and modeling microfluidic systems.

As the length scale of the fluid domain reaches the microscale level (1-100 μm) and below, several unusual phenomena that are not observed at the larger scales appear. One of the significant changes due to the very small length scale occurs at the fluid-solid boundary. Fluids, particularly polymer systems and suspensions, may slip or appear to slip at the fluid-solid interface [1] leading to the invalidity of the no-slip boundary condition, which is commonly assumed in conventional flow modeling. The wall slip occurring in the microflow changes the flow field of the fluid resulting in the apparent reduced viscosity of the fluids. These microscopic phenomena can be explained by the characteristics of the microflow including: (i) high surface-to-volume ratio, (ii) high rate-of-deformation (e.g. high shear rate and high extensional rate), (iii) high heat and mass transfer rate, and (iv) low Reynolds number (*Re*).

2 EXPERIMENTAL SETUP

A slit rheometer is suitable for the rheological measurement of microfluidics because it can measure the viscosity at high shear rates, it is geometrically and fundamentally similar to the relevant flow, and it is relatively easy to fabricate a micrometer-sized channel gap. An experimental setup of a customized microslit rheometer is shown in Figure 1 and consists of: (i) a microslit die, (ii) a high-precision syringe pump with an on-pump pressure transducer, (iii) a data acquisition system, and (iv) heating tape for high temperature measurement.

The microslit die with a micrometer-sized channel gap was built by machining a shim stock of stainless steel following the channel design and clamping it between two die halves (25 mm thick each) made of tool steel. The thickness of the channel gaps is then defined by the thickness of the shim stocks (25 μm and 100 μm thick). The microslit die was connected to the syringe pump via stainless steel tubing (6.35 mm ID). The high precision syringe pump was used to drive the fluid through the microchannel of the microslit die at a given volumetric flow rate. The fluid flowed from the pump into the tubing, and then into the microchannel of the microslit die and exited at the end of the die, where the fluid was collected in a container underneath the die.

The total pressure drop (Δp_{tot}) in the flow system was measured by the on-pump pressure transducer and monitored by a data acquisition system (LabView version 7.1) to find out the pressure drop at steady state. The total pressure drop was corrected by the end pressure drop (Δp_{end}) to obtain the pressure drop across the channel (Δp). For higher temperature testing, heating tape with an adjustable power controller was used and wrapped around the tubing and the die to increase the operating temperature (50°C). The setting temperatures were controlled at the inlet, where the material flows into the die, by a surface thermometer.

A shim stock-based microslit die offers numerous advantages including: (i) low cost in materials and manufacturing, (ii) simple fabrication with short production time, and (iii) uniform channel thickness. However, the channel gap is limited by the thickness of a shim stock because the thinnest shim stock commercially available is 12.5 μm thick.

3 RHEOLOGICAL MODELS

Rheological models for the microslit rheometer were derived to calculate the viscosity of the suspension fluid at the microscale level using no-slip and slip boundary conditions. The no-slip boundary condition (Figure 2a) assumes that there is no relative motion at the solid-fluid boundary. In the pressure-driven flow, where the fluid flow is due only to the pressure difference with no motion of the wall, the no-slip condition assumes that the velocities of the fluid at the wall equal zero. This is shown as follows:

$$v_x = 0 \, , \; v_y = 0 \tag{1}$$

where v_x and v_y are the velocity of the fluid in the flow direction (x) and the perpendicular flow direction (y), respectively, as shown in Figure 2a.

On the other hand, the slip boundary condition (Figure 2b) in case of suspensions is motivated by the existence of a thin layer of lower viscosity fluid in contact with the solid wall. This slip condition is represented by the following relation [2]:

$$\tau_w = \lambda v_s \tag{2}$$

where τ_w is the shear stress at the wall, λ is the friction coefficient at the wall, and v_s is the slip velocity in the flow direction at the wall.

Therefore, we obtain

$$v_s = \frac{\eta}{\lambda} \left. \frac{dv_x}{dx} \right|_w \tag{3-a}$$

$$v_s = \beta \left. \frac{dv_x}{dx} \right|_w \tag{3-b}$$

where η is the fluid viscosity, $\frac{dv_x}{dx}$ is the velocity gradient, and $\beta = \frac{\eta}{\lambda}$ is the slip parameter known as slip length.

The concept of the slit rheometer is based on the pressure-driven flow of a fluid between two stationary parallel plates with a gap (H). The fluid flows due only to the pressure drop across the channel (Δp) at a given volumetric flow rate (Q) in a rectangular channel with width (W), length (L), and height (H) where $H << W$ and L. The rheological models for slit rheometers [3] – including the shear stress (τ_w), shear rate ($\dot{\gamma}_w$) at the wall, and shear viscosity (η) – are summarized in the following:

No slip boundary condition (Equation 1):

$$\tau_w = \frac{H}{2L} \Delta P \tag{4-NS}$$

$$\dot{\gamma}_w = \frac{2}{WH^2} \left(2Q + \Delta P \frac{dQ}{d\Delta P} \right) \tag{5-NS}$$

Slip boundary condition (Equation 3b)

$$\tau_w = \frac{H}{2L} \Delta P \tag{4-SL}$$

$$\dot{\gamma}_w = \frac{2}{WH^2 \left(1 - \frac{4\beta}{H} \right)} \left(2Q + \Delta P \frac{dQ}{d\Delta P} \right) \tag{5-SL}$$

The shear viscosity is defined by

$$\eta = \frac{\tau_w}{\dot{\gamma}_w} \tag{6}$$

4 VISCOSITY MEASUREMENT

The microslit rheometer was used to measure the viscosity of (i) a Newtonian fluid: antifreeze and (ii) a non-Newtonian fluid: carbon black suspension. To verify the data, the viscosity of both fluids obtained from the microslit rheometer was compared with the data measured from a commercial 1-mm-gap parallel disc Physica MCR 300 rheometer (from Anton Paar) at high shear rates.

4.1 Viscosity of antifreeze

The viscosity measurement of antifreeze was conducted at room temperature (~25 °C) and plotted against the shear rate as shown in Figure 3. By using the developed microslit rheometer, the viscosity data of the antifreeze was obtained at a high shear rate up to 10^6 s^{-1}. There is no indication of shear thinning or a reduced viscosity due to wall slip in both 25-μm and 100-μm channel gaps. This implies that, for antifreeze, wall slip does not occur in channel gaps at either the macroscopic scale (1 mm thick) or the microscopic scale (25 μm and 100 μm thick).

4.2 Viscosity of carbon black suspension

The viscosity of the carbon black dilute suspension was measured by the microslit rheometer in various conditions. Variables used in this experiment include: (i) channel gaps: 25 μm and 100 μm, and (ii) operating temperatures: 25°C and 50°C. The viscosity measurements at temperatures of 25°C and 50°C are displayed in Figures 4 and 5, respectively. The experimental results show the reduced viscosity of the suspension fluid in the 25-μm channel gap, which indicates the evidence of wall slip in this length scale of the channel.

5 ANALYSIS OF THE WALL SLIP

The reduced viscosity of the suspension found in the 25-μm channel gap indicates the wall slip in the fluid flow. The developed rheological models (Equations 4, 5, and 6) were used to analyze the viscosity data and determine the values of the slip parameter, known as slip length (β). The average values of the slip length in the 25-μm channel gap at temperatures of 25°C and 50°C are summarized in Table 1. This value of the slip length is then used to correct the wall slip to obtain the true viscosity of the suspension fluid, which is independent of the channel sizes. The value of the slip length is also needed in the numerical solution to accurately predict the pressure flow of the suspension fluid in microchannels. The viscosity of the suspension fluid at 25°C and 50°C after the slip correction is shown in Figures 6 and 7, respectively.

6 CONCLUSIONS AND FUTURE WORK

According to the viscosity data measured using the microslit rheometer, a reduced viscosity was found in the 25-μm-gap microchannel at 25°C and 50°C. The reduced viscosity indicates wall slip of the carbon black suspension in the 25-μm-gap channel. The developed rheological models were used to analyze the viscosity data at the differently-sized microchannels (25-μm and 100-μm gaps) and determine the average values of the slip parameter, known as slip length (β). This value of the slip length is then used to account for wall slip in order to obtain the true viscosity of the suspension, which is independent of the channel sizes. The value of the slip length is also needed in the numerical solution to accurately predict the pressure flow of the suspension fluid in microchannels.

For future work, we will be employing high-speed confocal microscopy to obtain data that can be used for microscale confocal particle image velocimetry ($\mu CPIV$). This will allow us to measure thin optical slices that can be reconstructed to give three-dimensional velocity profiles of the flow at steady state.

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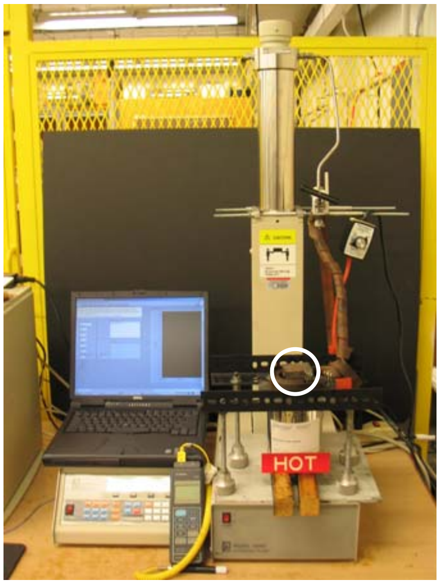
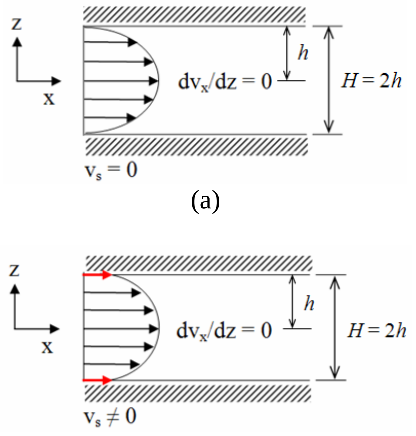


Figure 1: An experimental setup of the microslit rheometer



(a)

(b)

Figure 2: Schematic representation of (a) no slip boundary condition and (b) slip boundary condition.

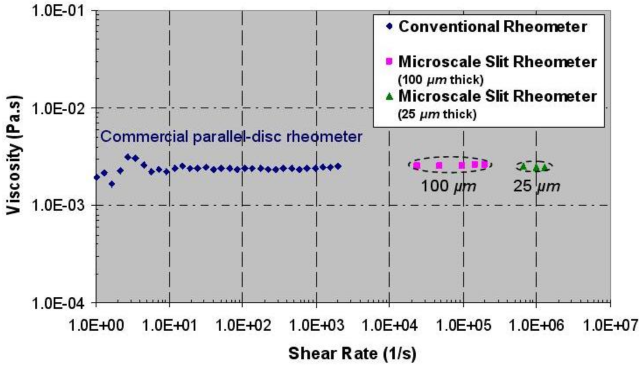


Figure 3: The viscosity measurement of antifreeze at 25°C.

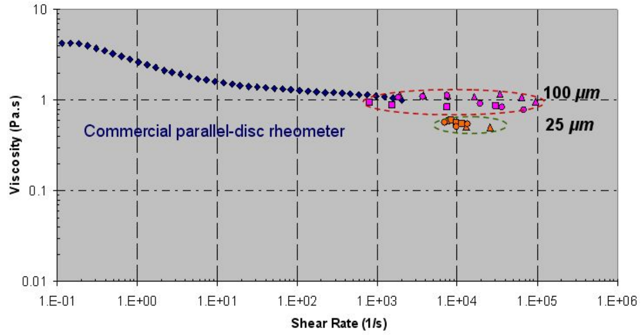


Figure 4: The viscosity measurement of the carbon black suspension at 25°C.

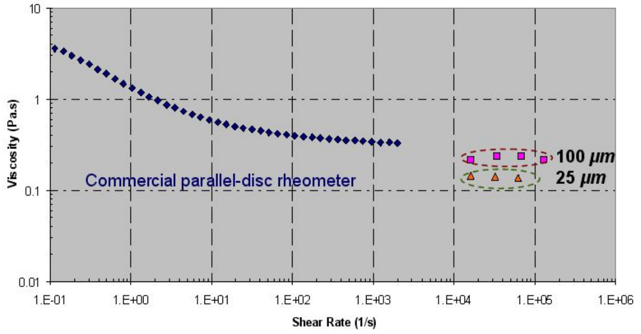


Figure 5: The viscosity measurement of the carbon black suspension at 50°C.

Channel Gap		Slip Length, Beta
1 mil (25.4 μm)	Temp 25°C	3.0 μm
	Temp 50°C	2.4 μm

Table 1: The average values of the slip length in the 25-μm channel gap at temperatures of 25°C and 50°C.

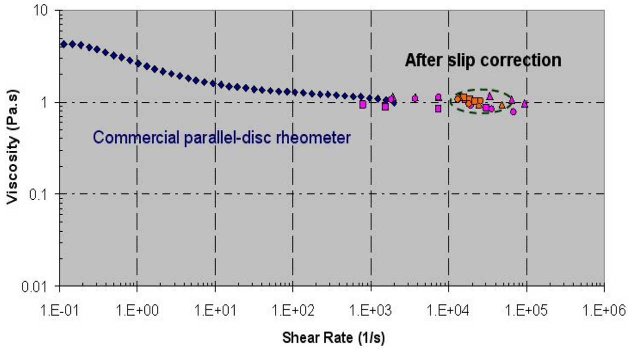


Figure 6: The viscosity of the carbon black suspension at 25°C after the slip correction.

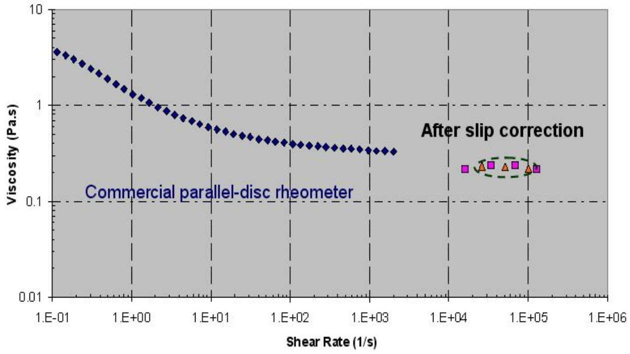


Figure 7: The viscosity of the carbon black suspension at 50°C after the slip correction.