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Electrokinetic effects of charged nanoparticles in microfluidic Couette flow

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ABSTRACT

The behavior of Couette flow of nanofluids composed of negatively-charged nanoparticles dispersed in aqueous NaCl solutions is studied theoretically. The equation for calculating the Couette flow velocity profiles is derived. The induced electric fields and velocity profiles are calculated as a function of key parameters including nanoparticle size and volume fraction. We have found for the first time that the velocity profile of nanofluids containing charged nanoparticles deviates significantly from the classical linear velocity profile for Couette flow. This previously unseen flow phenomenon is attributed to the dominance of the electric field strength induced by the flow of charged nanoparticles. This new mechanism of nanoparticle-induced microfluidic transport could lead to novel microfluidic and tribological applications.

1. Introduction

Nanofluids, a new class of nano-engineered liquid solutions of colloidal particles with a diameter of 1–100 nm, have been shown to have great energy savings potential [1] and attractive properties [2,3] for applications such as energy, bio and pharmaceutical industry, and chemical, electronic, environmental, material, medical and thermal engineering, among others [4–6]. In addition to the thermal properties of nanofluids, the rheological and tribological properties of nanofluids have been reported by several investigators. Lee et al. [7] added 0.1 vol.% of carbon nanomaterial C60 in mineral oil and showed an approximately 90% decrease in the friction coefficient. Battez et al. [8] showed both friction reduction and anti-wear characteristics by adding CuO nanoparticles in a polyalphaolefin (PAO6). Wong et al. [9] showed that the electric double layer (EDL) significantly increases the thickness of a thin lubrication film and reduces the friction coefficient of the lubrication film. When an electrolyte solution is convected through a microchannel under an applied external pressure gradient, an electrokinetic flow occurs in the direction opposite to the pressure-driven flow. As a result, the total flow rate is reduced and so the liquid appears to have a higher viscosity. The apparent increase in liquid viscosity is referred to as the electroviscous effect [10,11]. However, an electrokinetic flow enhancement effect would be much more interesting and desirable than the electroviscous retardation effect.

To our knowledge the electrokinetic flow enhancement effects have not been studied yet, especially for nanofluids having charged nanoparticles. The objective of this paper is to theoretically show the electrokinetic flow enhancement effects on plane Couette flow. To achieve the objective, we derived the equation for calculating the velocity distributions for Couette flow of electrolyte solutions with charged nanoparticles. Historically, many monumental discoveries have been made by scientists using the simplest models possible. Likewise, we have started off with a very simple model to study, for the first time, the effects of charged nanoparticles on the velocity distributions for plane Couette flow, one of the simplest types of flow.

Chemical Mechanical Planarization (CMP) is one of the major semiconductor manufacturing processes. During a CMP process, a slurry containing abrasive particles flows between two disks (wafer and polishing pad) [12]. This flow geometry can be thought of as plane Couette flow that was used to model the flow of abrasive particles in CMP slurries [13]. Hence, our results can be applied to study the flow of CMP slurries made of charged nanoparticles in an aqueous electrolyte solution and the effects of nanoparticles on the tribological properties of lubricants.

2. Analysis

2.1. Plane Couette flow system

One dimensional horizontal Couette flow is driven by moving the upper plate at a constant velocity (U) along the x-axis while the lower plate is kept stationary. The gap width between two parallel plates is in the range of 0.1–50 μm. The space between the two plates is filled with a nanofluids composed of negatively-charged nanoparticles uniformly dispersed in an aqueous NaCl solution. The surfaces of both plates are negatively charged. A

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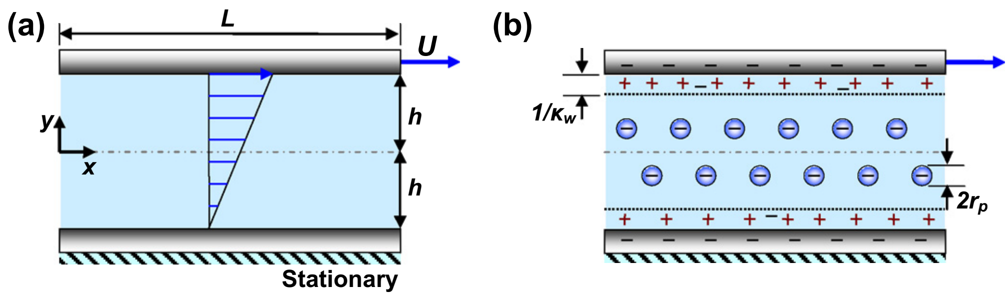

Fig. 1. Microfluidic plane Couette flow geometry and coordinate system: (a) the classical linear velocity profile for Couette flow, (b) the space between two parallel plates is filled with an aqueous NaCl solution containing uniformly dispersed negatively-charged nanoparticles.

schematic of the microfluidic Couette flow configuration is shown in Fig. 1. The classical linear velocity profile for Couette flow is shown in Fig. 1a. Aqueous NaCl solution containing negatively-charged nanoparticles and negatively-charged surfaces with an electric double layer at the solid–liquid interface are shown in Fig. 1b. The assumptions for our analysis are as follows: First, the flow is steady, laminar, and one dimensional ($u = u(y)$). Second, nanoparticles are monodisperse, rigid spheres with the radius r_p in the range of 3–50 nm, and homogeneously distributed in the solution. Third, interaction between charged nanoparticles in suspension is negligible because the concentration of nanoparticles is less than 0.4 vol.%.

2.2. Analytic solution

The Navier–Stokes equation modified to include the body force induced by the flow of charged nanoparticles in a nanofluid is given by

$$\mu_f \frac{d^2u}{dy^2} - \rho_e \frac{\partial \phi}{\partial x} = 0 \tag{1}$$

where μ_f is the viscosity of liquid, $\phi = \phi(x, y)$ is the electric potential, $-\partial\phi/\partial x = E_x$ is the strength of the induced electric field and ρ_e is the net charge density in the EDL. The net charge density is defined as $\rho_e = -2zen_b \sinh(ze\psi/kT)$ where z is the valence, e is the elementary charge, n_b is the bulk concentration of ion, ψ is the surface electric potential associated with the EDL of the wall/liquid interface, k is the Boltzmann constant and T is the absolute temperature. The boundary conditions for Eq. (1) are $u = U$ at $y = h$ and $u = 0$ at $y = -h$. Prior to obtaining a solution of the modified Navier–Stokes Eq. (1) to calculate the velocity profile, the net charge density in the EDL should be evaluated. Using Debye–Hükel approximation ($ze\psi/kT < 1$), the net charge density can be expressed as

$$\rho_e(y) = -\varepsilon\kappa_w^2\psi \tag{2}$$

where ε is the permittivity of liquid and $\kappa_w = (2n_b z^2 e^2/\varepsilon kT)^{1/2}$ is the Debye–Hükel parameter of the wall/liquid interface (the inverse of κ_w is the Debye length). In addition, ψ can be solved with the linearized Poisson–Boltzmann equation, $\nabla^2\psi = \kappa_w^2\psi$ and its boundary conditions $\psi_{wall} = \zeta_w$ at $y = \pm h$ where ζ_w is the zeta potential of the wall. With the solution of the electric potential [10], $\psi = \zeta_w \cosh(\kappa y)/\cosh(\kappa h)$, the net charge density is expressed as

$$\rho_e = -\varepsilon\kappa^2\zeta_w \frac{\cosh(\kappa y)}{\cosh(\kappa h)} \tag{3}$$

Consequently, the velocity profile in Couette flow of aqueous nanofluids with charged nanoparticles can be expressed as

$$u \equiv u_f(y) = \frac{U}{2}\left(\frac{y}{h} + 1\right) - \frac{\varepsilon\zeta_w}{\mu_f} E_x \left(1 - \frac{\cosh(\kappa_w y)}{\cosh(\kappa_w h)}\right) \tag{4}$$

As shown in Eq. (4) the velocity profile consists of two terms. The first term represents the classical linear velocity profile for Couette flow and the second term represents an additional velocity profile associated with the induced electric field E_x arising from the flow of charged nanoparticles. To calculate the velocity profile of the microfluidic Couette flow using Eq. (4), we should first evaluate the strength of the induced electric field E_x. In this study, streaming potential analysis [10,11] is used to derive E_x as described below.

The total electric current (I_t) that is generated by the flow of an electrolyte solution is made up of streaming current (I_{st}) and conduction current (I_c). Charge neutrality in steady-state Couette flow, in a microscale gap, requires that the net electrical current is zero.

$$I_t = I_{st} + I_c = 0 \tag{5}$$

Streaming current (I_{st}) is made up of the electric current generated by the Couette streaming of net ionic charges in the EDL ($I_{st,dl}$) and the electric current due to the movement of charged nanoparticles ($I_{st,p}$) as shown in Fig. 1b. In addition, conduction current (I_c) includes the bulk conduction current ($I_{c,b}$) which flows through the bulk solution and the surface conduction current ($I_{c,s}$) flowing through the wall/liquid interfaces. So, Eq. (5) can be rewritten as

$$I_t = (I_{st,dl} + I_{st,p}) + (I_{c,b} + I_{c,s}) = 0 \tag{6}$$

Electric current due to the movement of the net ionic charges in the EDL can be expressed as

$$I_{st,dl} = \int_A \rho_e u_f \, dA \tag{7}$$

Substituting Eqs. (3) and (4) into Eq. (7) one can obtain $I_{st,dl}$ as given by

$$I_{st,dl} = -\Omega\mu_f\kappa_w WU\tanh(\kappa_w h) + \Omega^2\mu_f\kappa_w WE_x\left[\tanh(\kappa_w h) - \frac{\kappa_w h}{\cosh^2(\kappa_w h)}\right] \tag{8}$$

where $\Omega = \varepsilon\zeta_w/\mu_f$ and W is the width of the plate.

The electric current due to the movement of charged nanoparticles ($I_{st,p}$) can be theoretically obtained as follows:

$$I_{st,p} = \int_A \rho_p u_p \, dA = \frac{q_s N_p}{V_t}\int_A u_p \, dA \tag{9}$$

where ρ_p is the charge density on the particle surface, u_p is the velocity of charged nanoparticles, q_s is the surface charge per nanoparticle, N_p is the number of particles and V_t is the total volume of the solution in the gap. The velocity of charged particles can be expressed as $u_p = u_{Cou} + u_{sp} + u_{ep}$ where u_{Cou} is the velocity in Couette flow of an aqueous solution containing no charged