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Measurement of liquid flow rate by self-generated electrokinetic potential on the microchannel surface of a solid

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ABSTRACT

A model to describe the interactions between the electrokinetic potential and the liquid ion slip is proposed. The model assumes that the electric charge at the liquid and solid interface causes an attraction force, whereas the fluid shear force at the wall induces a frictional force. Using the proposed model, the condition underlying liquid ion slip is described by analyzing the generation of the surface electric potential when the shear force of flow is above 0.1 mN. Once liquid ion slip occurs, the electric charges at the interface move in the direction of the flow but are retarded by electric resistance. Thus, there is a difference in the surface electric potential generated at the solid wall in the direction of the flow. In the water flowing through the microchannel, the velocity of the liquid ion slip was 5.09×10^{-5} to 2.19×10^{-3} m/s, whereas the generated surface electric potential varied from 0 to 64 μV. The proposed model and the experimental analyses provide the groundwork for precise flow sensors, which could easily be integrated into microfluidic systems.

1. Introduction

The application of microfluidic technologies has been explored in mechanical, chemical, and biological systems. Following the development of inkjet print heads in the 1980s, various applications of microfluidic devices were studied, such as DNA analysis, separation, cell analysis, immunoassays, microreactors, microfuel cells, sensors, and electronic cooling [1]. In general, most of the applications need sophisticated and efficient flow control and transport through micro/nano-sized channels. Given the small dimensions of these devices, the pressure drop will considerably increase with the flow rate to the third power of the channel height [2]. Moreover, as the dimensions of the channels continue to be reduced, surface forces induced by roughness, capillary, boundary slip, and chemical and electrical interactions begin to significantly affect the flow rather than gravitational or inertial forces. Recently, outstanding microscale flow sensors integrated with microfluidic devices have been reported. Microcantilever flow sensor was manufactured by using piezoresistive materials [3], while Demori et al. [4] developed an electrical capacitance sensor embedded in a microchannel to characterize the fluid based on the dielectric permittivity. Other capacitance sensors were proposed to detect the void fractions in microchannel flow [5]. The fundamental background of the sensors was the electrical potential variation related to fluid flow, that is, electrokinetic phenomena.

Electrokinetic phenomena play significant roles in many biological and electrochemical applications, such as vesicle motion, membrane fluctuations, electroporation, porous electrode charging, nanoscale detectors, and power cells [6–8]. Electrokinetic fluid delivery, cell positioning, mixing, separation, and DNA analysis have been widely applied in microfluidic devices [9,10]. Electrokinetic flow systems can be operated at lower pressure compared to conventional hydrodynamic systems [11]. As electrokinetic phenomena are associated with electric and fluid forces between the fluid and the solid interface [12], the interfacial interactions need to be understood. When the fluid is induced to flow by a pressure gradient, then some of the excess charge within the double layer is transported with the flow, giving rise to streaming current and potential [13]. In this regard, the well-known electrokinetic theory has been intensively studied. Streaming potential and current were measured across rectangular microchannel to characterize the zeta potential and surface conductivity [14]. Hydroxyl ion adsorption has been suggested to generate charges in electrokinetic flow at liquid and polymer interfaces [15]. In aqueous potassium solutions, the electrokinetic potential depends on the contact angle, the electrokinetic properties, the pH of the solution, and the surface charge density of the polymers [16]. In an analytical study of electro-osmotic flow through a circular microchannel with axial variations in both the electric potential and the hydrodynamic slip length, the presence of slip greatly amplified the

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increased dispersion caused by the pressure gradient and the non-uniformity of the wall potential [10]. Electro-osmotic flows through nonslip and slip regions have been studied to investigate the slip effect on the enhancement of the flow [2,17,18]. Researchers have also attempted to explain the slip effect on the electrokinetic phenomena in terms of the quasi-momentum of phonons [6] or fluctuation of Coulombic ions [19]. In a fluctuating Coulombic field, direct forcing of free electrons in solids was found to be responsible for the generation of the surface electric potential by liquid flowing through pulsating asymmetric ratchets, regardless of liquid ion slip [19]. The momentum of liquid flow was also shown to be transferred through the slipping layers to the solid wall, and the quasi-momentum of its phonons induced an electric current [6]. An alternative explanation has been proposed by Persson et al. [20]. Their model attributed the electric potential generation due to thermally activated jump of the ions based on the stick-slip model [21]. The degree of slip has been reported to be associated with a number of interfacial parameters, including the strength of the liquid–solid coupling, the thermal roughness of the interface, and the commensurability of the wall and liquid densities [22]. For example, the microtextured superhydrophobic surfaces were found to induce slip flow [23]. Molecular dynamic simulations have been conducted to investigate the role of slip flow that contributed to enhance the flow rate in carbon nanotubes or nanopipes [24–26]. According to a study of slip flow in a microscopic system, hydrodynamic and electrostatic double-layer forces should be taken into account to reach agreement between experimental and simulated results [27]. On the other hand, a vapor–liquid-like interface was suggested to cause anomalous electrokinetic effects and a nonzero zeta potential at uncharged surfaces [28].

Despite the previous works, electrokinetic phenomena are still not fully understood due to difficulties in characterizing chemical, physical, and electrical properties at the interfaces. Large discrepancies have been observed between classical electrokinetic theory and modern microfluidic experiments [29,30]. For example, a study of electrokinetic phenomena associated with hydrodynamic and hydrophilic slip surfaces yielded an unusual immobile Stern layer and an unexpected zeta potential [31]. The pre-existing models are hard to account for the surface electric potential generation caused by the fluid dynamic interaction between the liquid ions and solid surfaces. This study postulated that the microchannel flow is implicated in the liquid ion slip inducing the surface electric potential due to the electric resistance of the solid. The liquid ions begin to slip when the shear force of flow overcomes the attraction force between the ions and the electrons. The liquid ions are then driven by the shear force of flow at the wall but retarded by the electric resistance of the solid. The experimental results were compared with the analytical calculations based on the classical theory and the proposed model. It has been shown that the measured electrokinetic signals from the coated metal pads on the wall were successfully correlated with the proposed model. The proposed technology for sensing flow rate will be applied to precise flow sensors integrated into microfluidic devices without disturbing flow field or requiring external energy source.

2. Theory

When liquid is flowing through a channel as shown in Fig. 1, the streaming potential (ψ_{str}) and current (I_{str}) are caused by the zeta potential (ζ) of the well known Helmholtz–Smoluchowski equation [12,14]:

$$\psi_{str} = \frac{\zeta \varepsilon_0 \varepsilon_1 \Delta P}{(\mu K)} \quad (1)$$

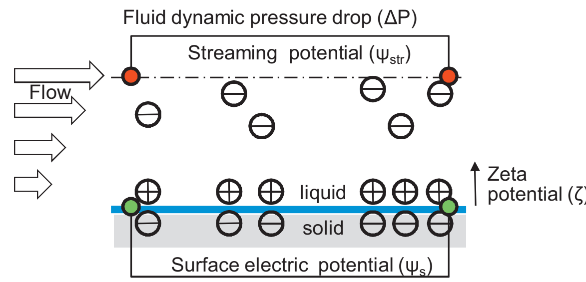

Fig. 1. Schematic of electron drag pinned by liquid ions. Streaming and surface electric potentials are generated due to the zeta potential.

$$I_{str} = \frac{\zeta \varepsilon_0 \varepsilon_1 D_w D_h \Delta P}{(\mu L)} \quad (2)$$

where ε_0, ε_1, μ, K, and L are the vacuum and liquid dielectric constants, and dynamic viscosity of the liquid, total conductivity, and channel length, respectively. In microchannels, the pressure drop (ΔP) can be theoretically predicted as a function of hydraulic diameter (D) defined by channel width (D_w) and height (D_h), $D = 2D_wD_h/(D_w + D_h)$ [32]:

$$\Delta P = \frac{2L\rho V^2 C_f}{D} \quad (3)$$

$$C_f Re = 4.7 + 19.64 \frac{\left[\left(\frac{D_w}{D_h}\right)^2 + 1\right]}{\left[\frac{D_w}{D_h} + 1\right]^2}, \quad Re = \frac{\rho V D}{\mu}$$

where V, ρ, C_f, and Re are average flow velocity, density of the liquid, friction factor, and Reynold number, respectively. The total conductivity (K) is expressed as the sum of a bulk liquid contribution and surface contribution [12]:

$$K = \frac{K_L + 4K_S}{D} \quad (4)$$

where K_L is bulk liquid conductivity. The surface contribution is caused by the fluid flow in the given geometry. To characterize the geometric effect of fluid flow on the surface conductivity, the surface contribution is defined by the ratio of surface conductivity (K_s) and hydraulic diameter (D) [33,34]. Although the surface electric potential difference along with the fluid flow has been studied to explain the generation of the electric field due to streaming potential; however, the interaction between liquid ions and solid surfaces was neglected [19,20]. In the current study, we consider liquid flow in a rectangular microchannel including the interaction between the liquid ions and the solid surfaces as depicted in Fig. 2. At stationary flow, the difference in the energy levels between the fluid and the solid leads to contact electrification [35]. The liquid ions are adsorbed at the interface where the counter electrons are attracted by the ions. Therefore, an attraction force between the ions and the electrons is generated due to the electric field, as illustrated in Fig. 2(b). When the liquid starts to flow, the adsorbed ions are forced to move by the shear force of flow at the wall. If the shear force overcomes the attraction force between the liquid and the solid, the liquid ions will slip against the wall. After the ions start to slip, the electrons at the solid surface are dragged by the ions while the momenta of the ions and the electrons are conserved across the interface. The ions at the liquid side are accelerated by the shear force of flow, whereas the electrons at the solid side are retarded by the electric resistance of the solid, which induces the lag of the electrons behind the ions, as shown in Fig. 2(c). Thus, the difference in the velocity of the ions and the electrons generates a surface electric potential upstream and downstream along the