Polydimethylsiloxane (PDMS) 마이크로채널 벽면의 계면동전기 유동에서 전단속도에 따른 Newtonian boundary slip 현상

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Shear-dependent Newtonian boundary slip in electrokinetic flow at polydimethylsiloxane (PDMS) microchannel walls

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Introduction

In general, Newtonian fluid slip at hydrophobic surfaces has been observed at the length scale of micrometers. Understanding of the physics of either microfluids or micro-rheology involving electrokinetic phenomena and fluid slip is needed for design and operation of flow in MEMS devices [1,2].

As proposed by Navier (1823) for liquids, a slip length β is defined at a rigid boundary with unit normal vector **n** directed into the fluid, relating linearly the velocity at the wall to the wall shear strain rate

$$v = \beta n \cdot \left[(\nabla v) + (\nabla v)^T \right] . \qquad (1)$$

The slip length is the local equivalent distance below the solid surface at which the no-slip boundary condition would be satisfied if the flow field were extended linearly outside of the physical domain [3]. The channel of microchip is almost always made by charged materials, such as glass, silicon, and plastics. The absence of slip would provide an increased drag on the flow due to the effect of electric double layer (EDL) in charged channels, resulting in an apparent viscosity which is higher than the true fluid viscosity referred to as the electroviscous effect. Both the electroviscous and fluid slip phenomena should be examined simultaneously since they have counter effects on fluid flow.

In this study, we consider the shear-dependent Newtonian slip with variations of the applied pressure drop in slit-like narrow channels. The velocity profile of dilute latex suspension in hydrophobic polydimethylsiloxane (PDMS) based microfluidic-chip is determined by applying the particle streak velocimetry (PSV) [4-6]. The slit-like channel has been fabricated by designing high aspect-ratio of the channel depth to the width that practically allows a parallel uniaxial flow.

Basic considerations

For incompressible laminar flow in the slit-like channel shown in Fig. 1, the velocity is expressed as $\mathbf{v}$ = [0, 0, $v_z(x)$] and the pressure p = p(z). After imposing the boundary conditions, we derive formulas of the velocity profile for no-slip and slip cases, respectively

$$v_z = \frac{(p_o - p_L)W^2}{2\mu L}\left[1-\left(\frac{x}{W}\right)^2\right] = \frac{3}{2}v_m\left[1-\left(\frac{x}{W}\right)^2\right], \tag{2a}$$

$$v_z = \frac{(p_o - p_L)W^2}{2\mu L}\left[1-\left(\frac{x}{W}\right)^2 + \left(\frac{2\beta}{W}\right)\right] = \frac{3}{2}v_m\left[1-\left(\frac{x}{W}\right)^2 + \left(\frac{2\beta}{W}\right)\right]. \tag{2b}$$

In Eq. (2b), the slip condition is expressed as $v_z|_{wall} = \pm\beta(\partial v_z/\partial x)|_{wall}$. The nominal shear rate defined at the wall is related to the average fluid velocity v_m as

$$\gamma|_{x=W} = -\frac{dv_z}{dx} = \frac{3v_m}{W}. \tag{3}$$

Flow visualization experiments and results

Microfabrication procedures based on the MEMS micromachining are employed to prepare the microfluidic-chip using molded PDMS and glass cover. The slit-like channel has been fabricated by designing high-aspect-ratio of the channel depth to the width that practically allows a parallel uniaxial flow. After the photoresist has been applied to the substrate, it is soft baked following with post exposure baking. With a master mold made at the Micro-Nano Fab. Center, a PDMS replica is prepared and then bonded with the glass cover shown in Fig. 2. The PSV adopted here involves recording particle displacements in a single image over a period of time, in which sparse quantitative particle velocity data can be obtained as reported in the literature. The velocity profile of dilute latex suspension was obtained in the microchannel, by employing the fluorescent microscope with PSV on a parallel uniaxial flow field. A ratio of particle size to channel width is quite small. In Fig. 3, particle streak imaging by fluorescent microscope are applied to a straight channel designed for dilute latex colloids underlying the condition of simple fluid.

Table 1 presents the hydrodynamic conditions obtained with changing the applied pressure drop, where the average fluid velocity increase with increasing pressure providing an increase of the nominal shear rate. Fig. 4 shows the behavior of velocity profile for different shear rates. Both walls of the channel correspond to PDMS which have highly hydrophobic feature, at which a slip velocity exists. The homogeneous surface condition results in a symmetric velocity profile in the PDMS chip. It is possible to estimate the slip length analyzing the data points nearby the PDMS wall along the regressions. For nominal shear rates less than about 30 s^{-1}, the slip length at PDMS surface can be identified ranging about 5.5 to 8 μm. If the nominal shear rate increases beyond this value, the slip length evidently changes. Note that this trend corresponds to the previous results [7].

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References

1. Barrat, J-L. and L. Bocquet, 1999, *Phys. Rev. Lett.*, **82**, 4671.
2. Tretheway, D.C. and C.D. Meinhart, 2002, *Phys. Fluids*, **14**, L9.
3. Lauga, E. and H.A. Stone, 2003, *J. Fluid Mech.*, **489**, 55.
4. Taylor, J.A. and E.S. Yeung, 1993, *Anal. Chem.* **65**, 2928.
5. Stone, H.A., A.D. Stroock and A. Ajdari, 2004, *Ann. Rev. Fluid Mech.*, **36**, 381.
6. Chun, M.-S. and S. Lee, 2005, *Coll. Surf. A: Physicochem. Eng. Aspects*, **267**, 84.
7. Zhu, Y, and S. Granick, 2002, *Phys. Rev. Lett.*, **88**, 106102.

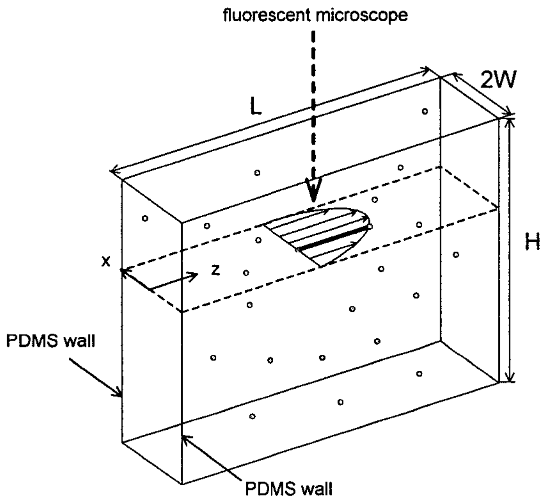

Fig. 1. Schematic volume containing the one-dimensional microflow of dilute colloidal suspension for particle streak imaging.

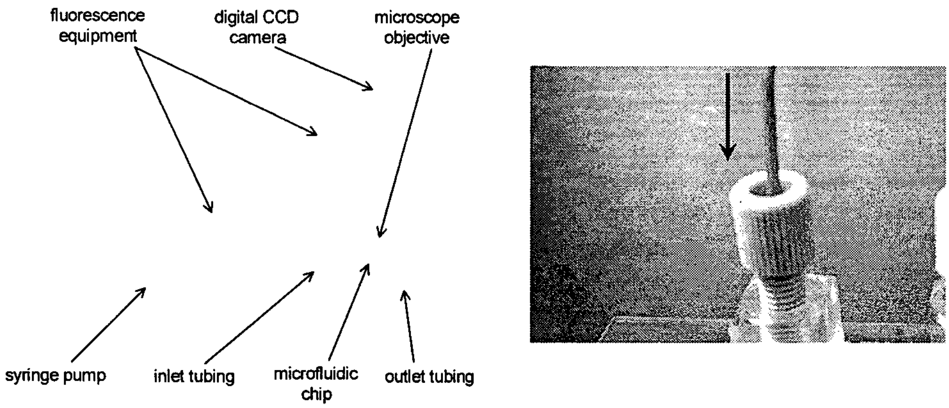

Fig. 2. Experimental setup (left), Microchip and tubing, where the PDMS replica bonded with glass coverslip forming the microchannel with 50 μm width and 250 μm height (right).

Table 1. Experimental conditions with different shear rates in the channel.

ΔP/L (Pa/m)	v_m (mm/s)	Nominal Shear Rate (s^{-1})	Reynolds No.	(Downstream) Flow Rate (μl/min)
5.6×10^2	0.1	14	0.01	0.08
2.4×10^3	0.5	60	0.04	0.33
4.8×10^3	1.0	120	0.08	0.67
9.6×10^3	2.0	241	0.17	1.30

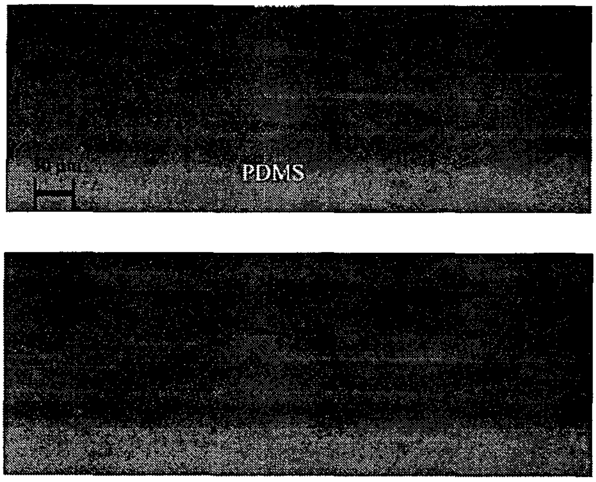

Fig. 3. Selected particle streak images in PDMS microchannel.

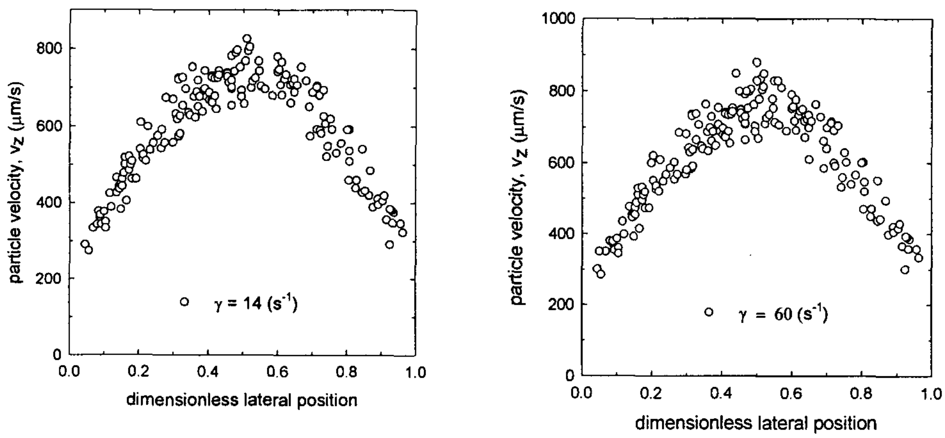

Fig. 4. Uniaxial velocity profile in slit-like channel of PDMS microfluidic-chip for different shear rates at pH 7 and 0.5 mM KCl electrolyte solution.