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Effect of Particle Migration of the Characteristics of Microchannel Flow

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Abstract: Experimental study was conducted to characterize the flow effect of particle migration in a microchannel which can be used to deliver small amount of liquids, drugs, biological agents and particles in microfluidic devices. Fluorescent particles of 1-μm diameter were used to obtain velocity profiles of the fluid in which large particles of 10-μm diameter were suspended at different volume fraction of 0.6 and 0.8%. Measurements were obtained by using micro-PIV system which contains a Nd:YAG laser with a light of 532-nm wavelength, an inverted epi-fluorescent microscope and a cooled CCD camera to record particle images. The volume fraction of the particle ϕ and the particle Reynolds number Re_p were used as a parameter to assess the influence of the velocity profile of the suspensions. To expect the slip velocity between the particle and fluids, experiments were carried out at low volume fraction. It was shown that the velocity profile was not influenced by Re_p but influenced by the volume fraction, which is in similar trend with the previous study.

Keywords: Particle migration, Micro-PIV, Microchannel.

1. Introduction

Microfluidic devices based on micro-electromechanical systems (MEMS) are being adopted in diverse engineering applications, such as micro valve, micro pump and, in particular, lab-on-a-chip which currently draws a lot of attention in bioengineering area. As is well known, most microfluidic devices may deliver particles less than several micrometers in size, such as microorganisms, drugs, even a DNA. By analyzing motions or distributions of particles moving through the microchannel, one can separate, sort, count and even manipulate particles. This can be done by exerting either external force, such as gravitational, electrical, thermal force, or no external force such as shear-induced force on particles. Masumi et al. (2004) showed that particles of different sizes can be separated continuously in a microchannel by only inducing shear force which causes a particle to migrate across the streamline of the flow field. Moreover, it was pointed out that particles through a microchannel can be counted more accurately by controlling lateral migration of the particles in micro total analysis system (Fuller et al., 2001).

In macro scale, the particle migration of a non-Brownian and neutrally buoyant particle was studied by Segre and Silberberg (1962) in a pipe with 5.5-mm radius. They observed that a rigid particle in a Poiseuille flow migrated to an equilibrium position located at r/a = 0.6, which was termed the *tubular pinch effect.* Their work triggered a series of experimental and theoretical studies to confirm particle migration in tube flow (Oliver et al., 1962; Goldsmith & Mason, 1967), in channel flow (Tachibana, 1973; Ho & Leal, 1974), in Couette flow (Halow & Wills, 1970). The origin of this effect lies in the inertia of the fluid, and lateral migration phenomena of the suspension in Newtonian fluids are expected to depend upon the particle volume fraction and the Reynolds number (Matas et al., 2004). In 2-D channel flow, the measurement demonstrated the existence of the blunting velocity profiles that were independent on the suspension flow rate at the volume fraction of 10~50%, but highly dependent on either particle volume fraction or the ratio of the particle size to the channel gap (Koh et al., 1994). However, the velocity profile presented so far is that of particles not liquids. One of the most interesting phenomena inferred from the study done by Koh et al. (1993) is that there exists a relatively large slip velocity between the particle and the fluid, which increases as the bulk particle concentration increases. Therefore, it is important that any measurement of the flow of suspensions should take these slip phenomena into account. Experiments should be conducted at very low volume concentration to investigate these slip phenomena. Most of the previous studies were done at high volume fraction where the slip phenomena can not be observed.

However, in micro scale, few studies have been carried out. It was reported that red blood cells (RBC) clearly exhibit the *tubular pinch effect* at high shear rate, but it disappears at low shear rate in a microchannel of 100-μm width (Wim et al., 1994). Recently, Frank et al. (2003) performed an investigation by varying ϕ and Peclet number, and reported that shear-induced Brownian particles migrate toward the center of the channel (50 μm × 500 μm), which means that the magnitude of the particle concentration is higher at the center of the channel than near the wall. But velocity profiles were not calculated in their studies.

In the present study, the effect of the particle migration on the velocity profile was conducted in a microchannel (100 μm × 1000 μm) that approximates two dimensional pressure-driven flow by using micro-PIV system which contains a Nd:YAG laser and an epi-fluorescent microscope equipped with a cooled CCD camera. Fluorescent particles of 1-μm diameter were used to obtain velocity profiles of the fluid in which large particles of 10-μmdiameter were suspended at different volume fraction of 0.6% and 0.8%. Particle Reynolds number and volume fraction were adopted as a parameter.

2. Experiment

The experimental apparatus shown in Fig. 1 consists of an epi-fluorescent optical microscope through which the green light (λ = 532 nm) is transmitted, a cooled CCD camera and a fluid feeding system. A set of the green light generated from the Nd:YAG laser passes through NA = 0.34 10× objective lens into the microchannel. Fluorescent polymer particles whose diameters are 1 μm, absorb the green light and emit a red light (λ = 570 nm). The remaining red light is focused by a lens onto a cooled 1030×1300×12 bit interline transfer CCD camera which acquires a pair of images at a rate of 10 frames per second. The microchannel was glued to a circular tube through which the liquid was fed by a syringe at various flow rates. For PIV analysis, two headed Nd:YAG laser allowed the cross-correlation of singly exposed image pairs acquired with microsecond time interval between two images. The interrogation window size is set at 32×32 pixels which gives spatial resolution of 10 μm in the streamwise direction, 20 μm spanwise direction. A 50% overlap between interrogation windows gives a velocity-vector spacing of 10 μm in the wall-normal direction. The velocity vectors of the 15 % of the channel width from the wall can not be obtained due to the optical effect at the corner of the channel. Ensemble-averaged velocity vectors were obtained by the cross-correlation of 100 pairs of images. The depth of field of the microscopic objective lens in the

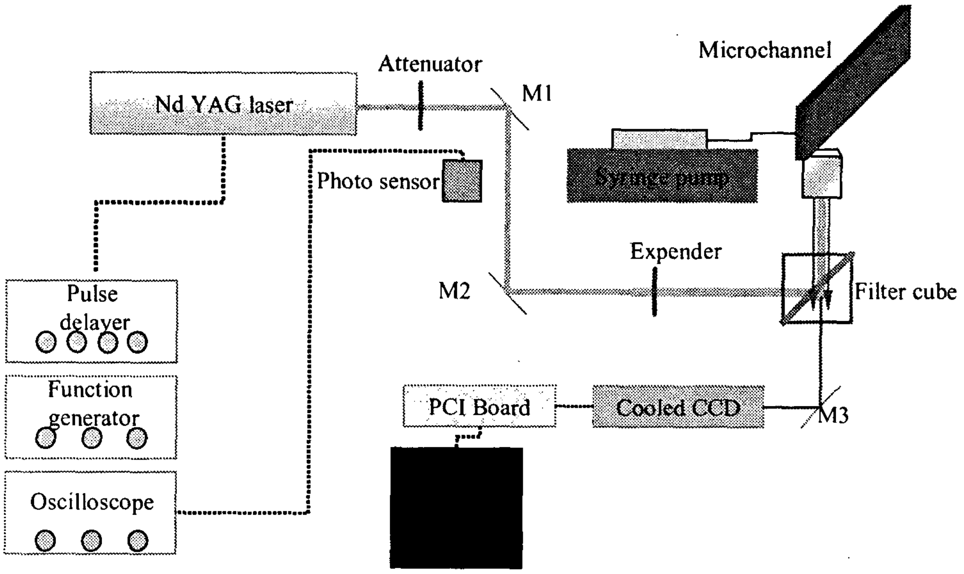

Fig 1 Schematic of the experimental system. A Nd:YAG laser is used to illuminate 1-μm fluorescent particles through an epi-fluorescent inverted microscope. A cooled CCD camera is used to record the particle images.

present study was estimated from the equation (1) given by Inoue & Spring (1997), where n is refractive index of the medium between the channel and the objective lens, λ is the wavelength of the laser, NA is the numerical aperture of the objective lens defined as $NA = n \times sin\theta$, e is the spacing between pixels of the CCD camera.

$$\delta z = \frac{n\lambda_0}{NA^2} + \frac{ne}{NA \cdot M}, \tag{1}$$

In bidisperse system, which means that the large particles of 10-μm diameter were mixed with fluorescent particles of 1-μm diameter, the density of the fluid was matched with that of the particle by using water-glycerin mixture. Also, Particle Reynolds number Re_p is defined in a manner analogous to that for tube flow (Goldsmith & Mason, 1967) as

$$Re_p = \frac{4}{3}\frac{\rho}{\mu}\frac{a^3}{H^2}V_{max} \tag{2}$$

where ρ is particle density, μ is the viscosity of liquid medium (water-glycerin mixture), a is the diameter of the large particle, H is the channel gap size, V_{max} is the maximum velocity of the fluid at the center of the channel.

4. Results and discussion

The goal of this study is to measure velocity profiles of the fluid possessing bidiperse particle distribution. The velocity can be measured by tracing small particles which are labeled with a fluorescent dye. Thus, it is expected that we estimate the effect of the particle migration on the flow characteristics of the fluid undergoing approximately two-dimensional pressure-driven channel flows. In the present work, two different volume flowrate were used, corresponding to the particle Reynolds number of 6.3×10^{-2} and 6.3×10^{-1}. The width of the channel was chosen as 100 μm, and two different volume fraction were considered, ϕ = 0.6 and 0.8%. All of the data reported here were obtained from the images of the plane approximately 500 μm from the bottom of the channel wall, at the position 25mm from the entrance of the channel.

Prior to measurements of the suspension, micro-PIV technique was tested by measuring the velocity profiles of the fluid in which large particles are not suspended. Because channel aspect ratio of 0.01 was utilized, the flow across the channel gap was approximately two-dimensional, and therefore, nearly parabolic velocity profile was expected. Fig. 2 shows the velocity profiles obtained by using micro-PIV technique, which are normalized by the maximum velocity of the centerline, V_{max}, and the solid line indicates the theoretical parabolic fitting. Each marker represents experimental values, which gives an agreement with theoretical value. However, near the wall, velocity data could not be obtained due to the optical effect.

Fig. 3 and 4 shows the velocity distribution of the fluid at different Re_p when the volume fraction of the large particle is 0.6 and 0.8%, respectively. As shown in Fig. 3 and 4, velocity profiles are not nearly influenced by Re_p, which was in similar trend with the previous study (Lyon & Leal, 1998) for velocity profiles of the large particle.

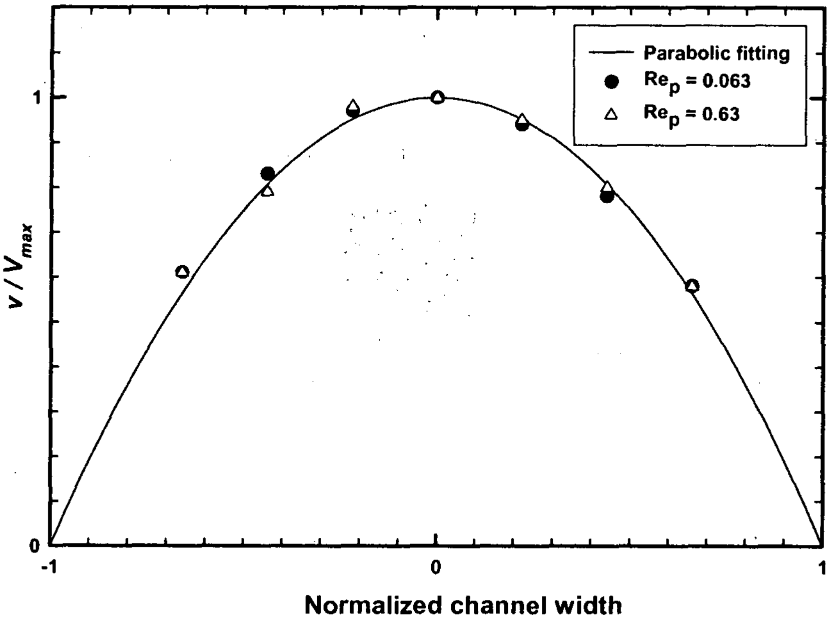

Fig. 2 velocity profiles for the fluid seeded with 1-μm fluorescent particles.

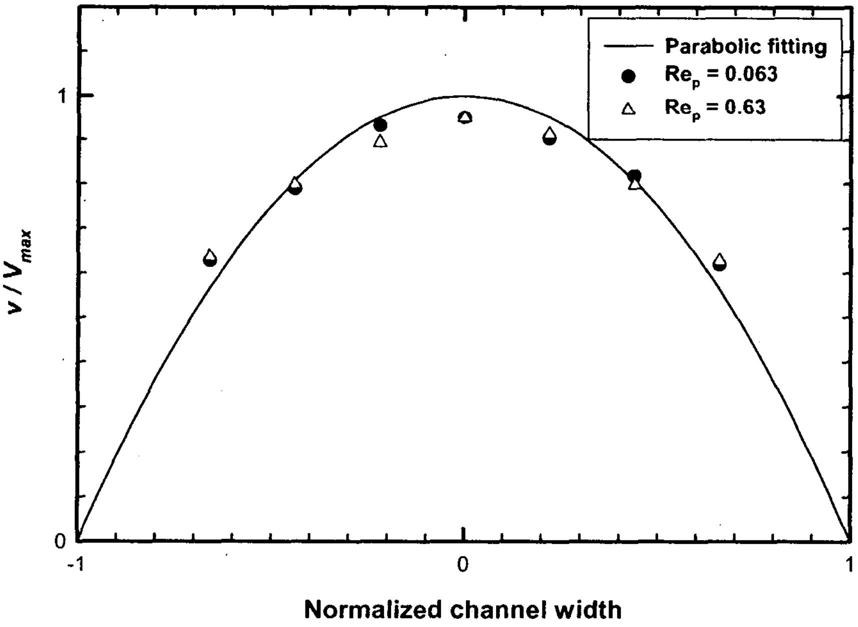

Fig. 3 Influence of Re_p on the velocity profiles of the fluid obtained by tracing 1-μm fluorescent particles mixed with large particles of 10-μm diameter. ϕ = 0.6 %.

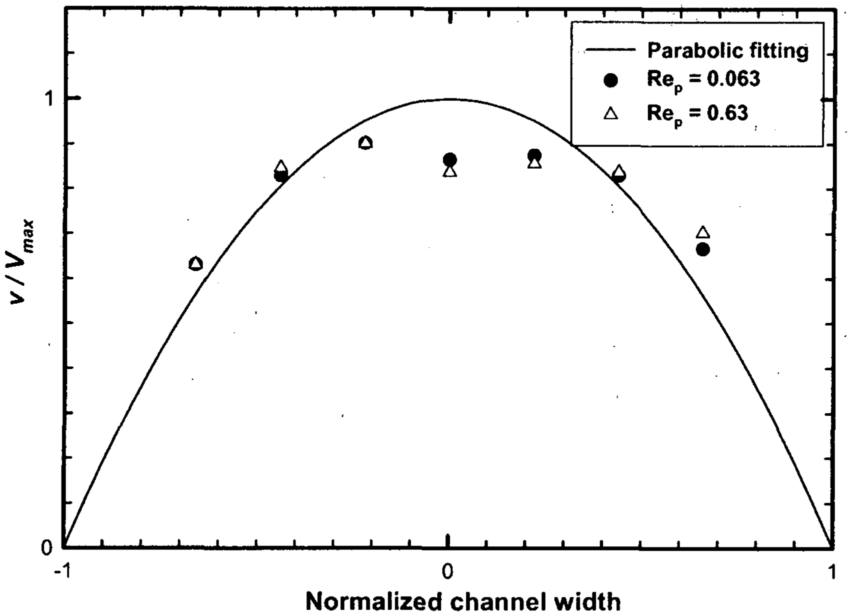

Fig. 4 Influence of Re_p on the velocity profiles of fluid obtained by tracing 1-um fluorescent particles mixed with large particles of 10-um diameter. ϕ = 0.8 %.

The velocity profile for the fluid is illustrated in Fig. 5 to evaluate the effect of the particle volume fraction. As can be seen in Fig. 5, experimental data for volume fraction of 0.6% are slightly deviated from theoretical curve at the center of the channel, while the values for 0.8% shows a pronounced blunting of the velocity profile, which was also similarly presented at high volume fraction of the large particle by Kho et al. (1994). The magnitude of this blunting effect increases with increasing of either the bulk particle concentration of the suspension or the ratio of the particle size to the width of the channel. It is interesting that the velocity profile of the particle was parabolic at the volume fraction lower than 10% in macro scale (Hookham, 1986). However, in the present study, the velocity profile of the fluid was blunted even at very low volume fraction of 0.8 %. We consider that it is not reasonable to directly compare our results with that done by previous studies (Hookham, 1986; Kho et al., 1994) since

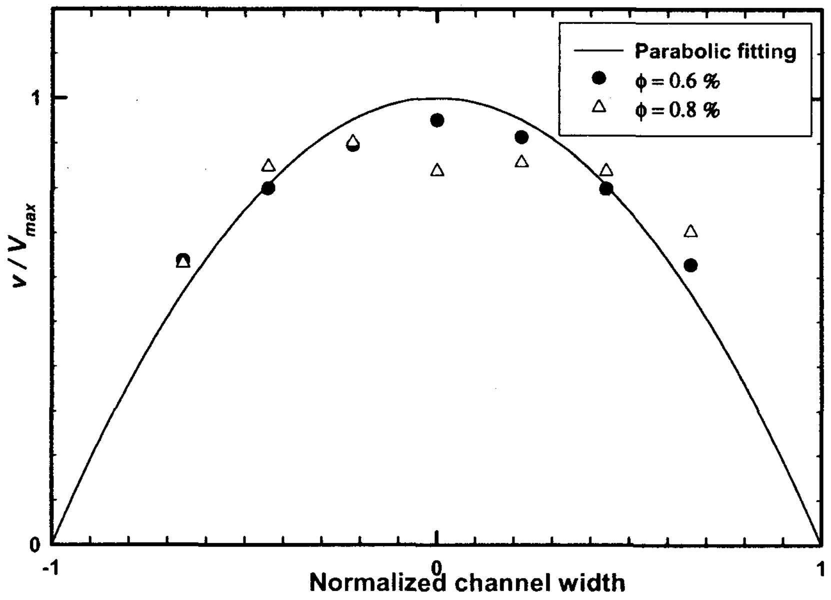

Fig. 5 Influence of particle volume fraction on the velocity profiles of liquid medium obtained by tracing 1-μm fluorescent particles mixed with large particles of 10-μm diameter. $Re_p = 6.3\times10^{-2}$.

the experiment in this study was carried out in micro scale at the $\mathrm{Re_p}$ and the H/a, which are much higher than those used in the previous studies.

5. Conclusions

In the present study, the effect of the particle migration on the velocity profile was conducted in a microchannel. Fluorescent particles of 1-μm diameter were used to obtain velocity profiles of the fluid where the large particles of 10-μm diameter were suspended at different volume fraction of 0.6 % and 0.8 %. To obtain the particle images, a Nd:YAG laser and an epi-fluorescence microscope equipped with a cooled CCD camera were used. It was shown that the velocity profiles of the liquid are not influenced by $\mathrm{Re_p}$ but highly influenced by the volume fraction. To explain the effect of the particle migration on the blunted profile of the fluid, it is necessary to obtain the profile of the particle velocity and concentration, which will be presented in our future study. It is also interesting to investigate the slip phenomena between the fluid and the particles by obtaining the velocity profile of the large particles since the velocity of a single particle will always be less than that of the fluid owing to interactions with the channel walls, which can be done at very low volume fraction of particles.

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