Flow Characteristics of Neutrally Buoyant Particles in 2-Dimensional Poiseuille Flow through Circular Capillaries

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Abstract

An experimental study has been conducted to quantitatively characterize the motion of neutrally buoyant particles in 2-dimensional Poiseuille flow through the micron-sized circular capillaries in the range of Re (Reynolds number) ≈ 0.1 ~ 100. A μ-PTV (Particle Tracking Velocimetry) system is adopted, which consists of a double-headed Nd:YAG laser, an epi-fluorescence microscope and a cooled CCD camera. Since high shear rate can be induced due to the scale effect even at low Re, it is shown that in micro scale neutrally buoyant particles in Poiseuille flow drift away from the wall and away from the center of the capillary. Consequently, particles accumulate at the equilibrium position of 0.52~0.64R with R being the radius of the capillary, which is analogous to that of tube flow in macro scale. There is a plateau in equilibrium position at small Re, while equilibrium position starts increasing at Re ≈ 30. The outermost edge of particle cluster is closer to the center of the capillary than that in previous studies due to low Re effect. The present study quantitatively presents characteristics of particle motion in circular capillaries. Furthermore, it is expected to give optimum factors for designing microfluidic systems that are to be used for plasma separation from the blood.

Key Words : Neutrally buoyant particle, Circular capillary, Particle motion

1. Introduction

Microfluidic devices, e.g. valves, pumps, mixers and so on, which can be integrated in LOC (lab-on-a-chip) commonly transport particulate materials. In most LOC devices, the range of the particle size passing through the microchannels is from several Angstroms for molecules to a hundred microns for macro molecules, but usually is less than *O* (10 μm ~ 100 μm). Since the fluid velocity inside of the channel is less than *O* (1 m/s), the Reynolds number (Re) is less than 30 in most devices (Stone and Kim, 2001). If the size of particles is large relative to that of the channel, the fluid flow is not single phase any more. In this case, there is a slip velocity between the fluid and the particle. To obtain the best performance of the devices where the two-phase flow is typically observed, it is necessary to study both the motion of the fluid and the behavior of the particles (Fuller et al., 2000).

Segre and Silberberg (1962) observed that when the particles flow through the circular tube, they drift away from the center of the tube and away from the tube wall, and consequently they accumulate at about r / R = 0.6 where R is the radius of the tube, unless the particle is so small that its relative motion with respect to the fluid is negligible. This phenomenon is termed "Tubular Pinch Effect" or "Segre and Silberberg Effect" and their work triggered a series of experimental and theoretical studies to confirm particle migration in tube flow (Oliver, 1962; Cox and Mason, 1971), in channel flow (Tachibana, 1973; Ho and Leal, 1974), in Couette flow (Halow and Wills, 1970). Ho and Leal (1974) first explained "Tubular Pinch Effect" by calculating the force acting on a sphere in 2-dimensional channel flow. However, before their work, particle migration of a neutrally buoyant sphere in Poiseuille flow could not be explained by existing theory. As the Re increases, equilibrium position shifts toward the wall and it is also found that there is multiple equilibrium positions (Asmolov, 1999; Matas et al., 2004). Joseph and Ocando (2002) investigated slip velocity between the fluid and the particle when the particle migrates. Particle motion of both neutrally and non-neutrally buoyant particle in Couette and Poiseuille flow has been summarized by Feng et al. (1994). Cho et al. (2005) conducted numerical simulation with many particles using direct numerical simulation (DNS). Chun and Ladd (2006) investigated particle migration by numerical simulation in a square channel in the range of

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Re =100 ~ 1000. Their result shows that particles are absent around the center of the channel at Re = 100 and are gathered in one of four stable positions near each corner at Re = 500. Particle motion under Poiseuille shear flow can be summarized as follows: particle lagging behind the fluid migrates toward the center of the channel, while that leading the fluid migrates toward the wall, and neutrally buoyant particle moves to its equilibrium position which is about mid-plane between the channel center and the wall.

Characteristic length scale of the studies mentioned above ranges from O (mm) to O (cm). In other words, only a few studies on the particle motion in Poiseuille flow have been carried out in micro scale. Staben and Davis (2005) investigated particle transport in narrow rectangular microchannels where the channel gap is 500 µm, when the order of particle size is similar to that of channel gap. Uijttewaal et al. (1994) showed that RBCs (Red Blood Cells) migrate as shear rate increases in rectangular glass capillary of 100-µm width. Some interesting issues in this study are to identify particle equilibrium position and outermost edge of particle cluster. Studies on these issues have been often carried out in terms of macro scale, while there are few reports made in terms of micro scale so far. However, when the particles are transported in microfluidic channels, the fluid flow induces particle migration across the streamlines because it is common that the particle size is large relative to that of the channel. Thus, the principle of particle migration in Poiseuille shear flow has been used to separate blood cells in glass capillary where the diameter of the capillary is 600 µm (Wickramasinghe et al., 2001; Rakow and Fernald, 1991), and to perform radial focusing of DNAs in glass capillaries (Zheng and Yeung, 2003). Moreover, in microchannels, it is important to quantitatively analyze particle motions in Poiseuille flow to improve plasma selectivity (Jaggi et al., 2006; Yang et al., 2006), to minimize particle clogging (Vandelinder and Groisman, 2006) and to maximize total amount of plasma when the plasma can be separated from the whole blood in microfluidic devices. Although the cross section of the most microfluidic devices is rectangular, the motion of the particles in circular capillaries is similar to that in rectangular channels (Brenner, 1966). Thus, it is necessary to examine particle motions and to quantify their characteristics in circular capillaries.

In the present study, an experimental study has been quantitatively conducted to characterize particle motions in Poiseuille flow through the circular microchannels, For the experiments, we use µ-PTV (Particle Tracking Velocimetry) systems (Jin et al., 2004) which mainly consists of a fluorescence microscope, a cooled CCD camera and a two-headed Nd:YAG laser.

2. Experiments

Experimental apparatus consists of a double-headed Nd:YAG laser (Continuum Electro-Optics, Inc., CA, USA), an epi-fluorescence microscope (Olympus, Japan) and a cooled CCD camera (PCO, Germany) combined with the microscope. The laser used produces green light with a wavelength of 532 nm and pulse duration of 4 ~ 6 nm, which sufficiently freezes the motion of the particles at high velocity. The power of the laser light was reduced through the attenuator, which was directed via mirrors onto the upper side of the small chamber where the circular capillary was placed. The red light (λ = 612 nm) emitted from the particles, which is excited by green light (λ = 532 nm) was focused by the objective lens, and introduced into the CCD camera through the filter cube. This filter cube, placed in the microscope, blocks the scattered light that causes a noise of the particle images.

Dried particles which correspond to large target particles will not be mixed well with the water-glycerol mixture without any surface treatment. Therefore, as a surface-active agent, 100 µL of isopropyl alcohol (Sigma Aldrich, MO, USA) from a micropipette was added into the cleaned glass bottle that contains a small amount of dried fluorescent particles. Then, the water-glycerol mixture was added into the bottle until particle volume fraction reaches about 0.1 %. At this volume fraction, particle-to-particle interaction can be neglected when the particles are being transported with the fluid. The bottle containing the suspension was put into the water tank of ultrasonic cleaner (Branson, CT, USA) under operation for 20 min to prevent particle aggregation. Then, 1-mL disposable plastic syringe was filled with the particulate solution without any air bubble, then the syringe was connected with the upstream end of the capillary via Luer-Lock connector. Syringe plunger was depressed manually until the downstream end of the capillary which is open in the atmosphere becomes filled with the solution. The syringe was then placed a little tightly on syringe holder of the syringe driver (KD Science, MA, USA). The control panels on the syringe driver can be set at the desired flow rate. The CCD camera with a 1300×1024 pixel array and 12-bit resolution was connected to the image-grabbing board mounted on a personal computer, and 700 sets of particle images with TIFF format were obtained after the flow became stable at a given flow rate and at a frequency of 5 Hz.

3. Results and discussion

Regarding the particle motion due to inertial migration in macro scale, it is of great interest to investigate particle equilibrium position and outermost edge of particle cluster. However, it has been insufficiently reported in the case of micro-scale flow, despite the fact that it should be still taken into consideration with regard to its applications to microfluidics.

Equilibrium position is the radial position where the maximum PDF value of the particles appears. In general, the equilibrium position shifts toward the wall as Re increases in the previous experiments in macro scale

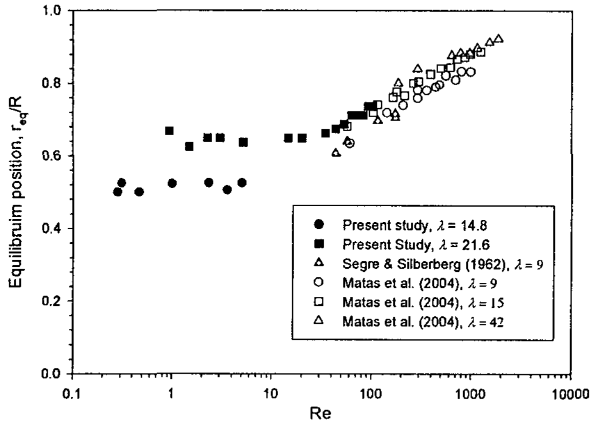

Fig. 1 Comparison of the equilibrium positions. All the previous studies are carried out in macro scale.

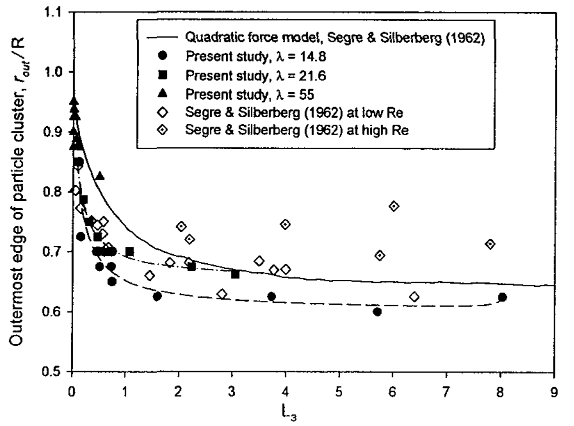

Fig. 2 Outermost edge of the particle cluster is shown as a function of L_3. Long-dashed and dashed-dot lines represent best curve fitting for λ = 14.8 and 21.6, respectively.

(Matas et al., 2004; Segre and Silberberg, 1962), as shown in Fig. 1. However, in the present study, there is a plateau in equilibrium position at small ranges of Re, while the equilibrium position starts increasing at Re ≈ 30, which has been proposed by Schonberg and Hinch (1989) in their numerical work. The equilibrium position shifts toward the wall if the outward force which pushes the particle toward the wall overwhelms the inward force such as wall repulsion, Saffman lift force and Magnus effect, originated from the existence of the wall (Ho and Leal, 1974). But in the small Re which is less than the order of 30 in the present study, the equilibrium position is rarely influenced by Re since the inward and outward forces are balanced at this range of Re. In addition to Re, equilibrium position can also be affected by λ. That is, if λ is small, the equilibrium position is closer to the center of the tube (Karnis et al., 1966), which is manifested from Fig. 1.

Now, we consider outermost edge of particle cluster and discuss its applications. Outermost edge of particle cluster, r_{out}, was defined by Segre and Silberberg (1962) as the maximum particle distance from the center of the tube. Outermost edge of particle cluster scaled by R, is shown in Fig. 2 as a function of L_3, defined by Segre and Silberberg (1962) as

$$L_3 = \left(\frac{D}{D_t}\right)^3 \left(\frac{l}{D_t}\right) \mathrm{Re}, \qquad (1)$$

where l is the measurement station from the inlet. As shown in Fig. 2, experimental results obtained in the present study are in good agreement with those of Segre and Silberberg (1962) except their data at high Re. They defined a new dimensionless parameter, L_3, to represent the variation of r_{out}. In other words, it was intended that the effect of individual factors of the right-hand side term in Eq. (1) on r_{out} would be vanished. However, in our results, the effect of λ on r_{out}, the first factor of the right-hand side term in Eq. (1) appears to still remain in Fig. 2: it is observed that there is some discrepancy of r_{out} between $\lambda = 14.8$ and $\lambda = 21.6$. Here, we consider that the particle-free layer thickness from the wall can be determined by subtracting r_{out} from R. In microfluidic devices where plasma is separated from the blood, the main technique is to extract plasma from the volume of particle-free region (Jaggi et al., 2006; Yang et al., 2006; Vandelinder and Groisman, 2006). It is expected that the best performance can be achieved by making the particle-free layer thickness as enlarged as possible for the higher plasma selectivity with the large amount of plasma. In the present study, as in most microfuidic channels, l/D_t is large relative to that of Segre and Silberberg (1962), which indicates that we can increase particle-free layer thickness, since L_3 should be increased without increasing Re.

4. Conclusions

An investigation is carried out to quantitatively characterize the motion of neutrally buoyant particles through circular capillaries in micro scale by applying μ-PTV technique at the Reynolds number range of Re ≈ 0.1 ~ 100. It is shown that particles accumulate at certain equilibrium positions of 0.52 ~ 0.64R, with R being the radius of the capillary, which is analogous to what is observed in macro scale at high Re. Equilibrium position starts increasing at critical Re ≈ 30, which is analogous to previous studies. The location of r_{out} which is important in relation to microfluidics, is closer to the center of the capillary than that of previous studies due to low Re effect. Further, it is indicated that plasma selectivity and total amount of plasma separated can be determined at the value of L_3 we address, when serum from the whole blood is separated into side channels in lab-on-a-chip systems, by minimizing the clogging of RBCs (Red Blood Cells). The present study is expected to give optimum factors for designing microfluidic systems.

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