Measurement of Particle Migration in Micro Channel by Multi Capacitance Sensing Method

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Abstract:

Study of particle migration is important to enhancement and increases the efficiency of the positioning and sorting process in order to produce the high yield of desired product especially in microfluidic applications. In this study, in order to study particle migration, normalized particle concentration in a micro channel has been calculated for high initial particle concentrations ($\zeta=3.0, 5.0$ and 10.0%) and the small particle diameters ($d_p=1.3, 1.5$ and $2.1\ \mu\text{m}$) by using capacitance data measured by multi capacitance sensing method. From the calculations, it has been observed that the particle concentration at the wall vicinity area is increased as ζ and d_p are increased while the particle concentration at the center area is decreased. To analyze the tendency of the particle migration, two quantitative indicators are introduced, viz., streamwise migration ratio (Ψ) which is the ratio of particle concentration at the downstream to the upstream cross-section position, and the cross-sectional migration ratio (Φ) which is the ratio of the particle concentration at the wall to the center area at the same cross-sectional position. The result shows that the Ψ at the center area is decreased as the particles move along the channel irrespective of ζ and d_p while the Ψ at the wall vicinity area is increased. Based on Ψ and Φ , it has been observed that the particle migrate from the center area towards the wall vicinity area in the case of low ζ and small d_p while the particles tend to concentrate on the center area in the case of high ζ and the large d_p . As a result, the particle concentration at center is higher in the case of the lower ζ and the smaller d_p than that in the case of higher ζ and the larger d_p .

Keywords: Particle concentration, Micro channel, Multi layered sensor electrodes, Multi capacitance sensing, Particle migration, Streamwise migration ratio, Cross-sectional migration ratio

Nomenclature

ζ	initial particle concentration [v/v%]
d_p	particle diameter [μm]
Ψ	streamwise migration ratio
Φ	cross-sectional migration ratio
$(1-\phi)$	calculated particle concentration [v/v%]
D	width micro channel
l	length

A	area
z	cross-section position
ϵ	permittivity
C	capacitance
$K(\omega)$	Clausius Mossotti
E	electrical field

1. Introduction

Passive cell positioning and sorting methods are important to develop biological and medical systems. Recently, a microfluidic device has been demonstrated to be an effective method for passively positioning and sorting cells/particles without assistance of sheath fluid [1]. Normally, the ratio of a micro channel width D of the microfluidic device to the particle diameter d_p is relatively small and operates in the low Reynolds number, Re . Under this flow condition, the particles do not follow the fluid streamline and move to the certain equilibrium position. This phenomena is called particle migration. Many studies have investigated the behaviour of the particle migration in a micro channel theoretically [2-3], using numerical simulation [4-15] and by an experiments under certain conditions [16-17]. Under the certain conditions, the enhancement of the particle migration increases the efficiency of the positioning and sorting process in order to produce the high yield of desired product in the microfluidic applications. The conventional methods for the positioning and sorting of the particles are based on the externally controlled migration. In such approaches, the positioning and sorting of the particles are carried out with the assistance of the external force such as the field flow fractionation, hydrodynamic chromatography, electrophoresis [16], dielectrophoresis, acoustic separation and etc. However, these conventional methods based on the externally controlled migration require active sources to produce external force fields that makes the micro channel fabrication complex to be integrated to the lab-on-a-chip components.

To overcome the limitation of the conventional methods, other methods such as the inertial particle migration (without the assistance of the external force) in the pressure driven flows were studied and reported to have achieved high throughput particle migration [4-6, 9-12]. Since then, the inertial particle migration in a micro channel has received much attention due to its promising applications, such as the membrane free passive separation of particles or cells. In the inertial migration mechanism, the particles suspended in the fluid flowing through a micro channel experience a viscous drag and inertial lift forces [10-12]. The drag forces, mainly due to the viscosity of the fluid, are responsible for entraining the particles along the flow. The inertial lift forces are responsible for the crosswise migration of the particles across the streamline. On other hand, in the case of the existence of the particle rotation, the Magnus lift force [3] is applied. Thus, the parabolic laminar velocity profile produces a shear induced lift force and drives the particles away from the center towards the wall vicinity area. The flow velocity gradient is moderately low at the center area and higher at the area near the wall. Therefore, the shear induced lift force near the wall becomes stronger than at the center area. As the particles migrate close to the vicinity of the wall, a wall induced lift force is generated driving the particles away from the area in the wall vicinity. For instance, Zheng and Silber-Li [2] investigated the theoretical reason of the particle migration of $d_p=200$ nm, which is the influence of the Saffman lift force on the low initial particle concentration ξ under pressure driven deionized water flow. In a numerical simulation study, Frank et al. [4] investigated the inertial particle migration of $d_p=2$ μ m under very low ξ ; $\xi=0.05$ - 0.34 v/v % and found particles migrated toward the center in the case of $\xi=0.34$ v/v %. Also, by using constitutive modelling, Semwogerere et al. [5-6] investigated the inertial particle migration of $d_p=1.4, 2.3$ and 3.0 μ m under the low ξ ; $\xi=0.1$ - 0.4 v/v % and found that the particle concentration is decreased as ξ is increased.

On the other hand in order to investigate the effect of d_p , Hampton et al. [7] as well as Allende and Kalyon [8] investigated the effect of various d_p/D ratio ($d_p/D=0.0005$ - 0.02) under the low ξ ; $\xi=0.1$ - 0.5 v/v

% on the inertial particle migration and found that the particle concentration at the wall is increased with high d_p/D ratio. Also, Chun and Ladd [9] obtained the inertial particle migration of $d_p=2, 6$ and $10\ \mu\text{m}$ under the low $\xi=1.0\ \text{v/v}\%$ in relatively high $\text{Re}=100\text{-}1000$. According to their results, d_p is the dominant factor of the particle migration. Similarly, Carlo et al. [10] obtained the inertial particle migration of $d_p=9$ and $10\ \mu\text{m}$ precisely positioned in the three spatial dimensions within the crosswise plane of the channel and longitudinally in the regular chains along the flow direction. As well, Asgar et al. [11-12] demonstrated a spiral channel for diameter dependant focusing to enhance the inertial particle migration of $d_p=1.9, 10, 15$ and $20\ \mu\text{m}$ in very low $\xi=0.05\ \text{v/v}\%$ under $\text{Re}<50$. Also, Butler et al. [13] investigated the effect of various conditions including the d_p/D ratio ($d_p/D=0.00064$ and 0.00148) under the low ξ ; $\xi=0.4\ \text{v/v}\%$ and found that at the small d_p/D ratio, the particles were migrated towards the wall and for the large d_p/D ratio; the particles remained uniform along the channel wall. Besides, Pasquino et al. [14] found that the particle migration of $d_p=1.2\text{-}2.8\ \mu\text{m}$ and the alignment are strongly coupled phenomena. They reported that the smaller d_p , the shorter would be the required time for particles to migrate towards the wall area where the alignment takes place. Besides, Yong-Seok et al. [15] investigated the effect of $d_p=7\text{-}15\ \mu\text{m}$ in very low ξ ; $\xi=0.02\ \text{v/v}\%$ under $\text{Re}=4.7\text{-}120$ on the inertial particle migration. They found that the particles are focussed on the certain equilibrium position at near the wall vicinity area as the Re and d_p are increased. From these studies, it has been proved that as the d_p is increased, the inertial particle migration results to slightly higher concentration at the wall than at the center area.

However, most of the existing inertial particle migration studies are based on theoretical or numerical simulations. The experimental based studies are inadequate and are only under the low ξ to determine the inertial particle migration because of the difficulty of the conventional measurement method to measure the particle concentration under the high ξ . Typically, the light source that is used to measure the particle concentration in those experiments do not penetrate into the high ξ over $\xi=1.0\ \text{v/v}\%$, resulting the low accuracy measurement of the particle concentration. In order to overcome these difficulties, we developed the multi capacitance sensing method to determine the particle concentration in the high ξ [17]. To accomplish the goal, the micro channel was fabricated with 12 multi layered electrodes and quartz substrates by using the micro-electro-mechanical-systems (MEMS) processes. With the developed method, the spatial transition of the particle concentration distribution in $\xi=3.0\ \text{v/v}\%$ at the five normalized stream cross-sectional positions z^* were measured. As well, we investigated the particle concentration under the condition of the high $\xi=10.0\ \text{v/v}\%$ and the small d_p ($d_p=1.3, 1.5$ and $2.1\ \mu\text{m}$) [17]. Even though the inertial particle migration in the micro channel is a unique motion, the detail experimental observations of the dependency on the d_p and the locations of the cross-section are required to develop biomedical devices in the higher ξ condition.

In the present study, the streamwise migration ratio Ψ and the cross-sectional migration ratio Φ are introduced as quantitative indicators in order to determine the tendency of the inertial particle migration under the high ξ and small d_p . Both indicators were determined from the calculated normalized particle concentration $(1-\phi)$ measured by using the multi capacitance sensing method. These innovative approaches are introduced in order to determine the particle migration in a diamond shape cross-sectional micro channel under the high ξ and small d_p . In the micro channel embedding multi layered electrodes, the capacitances under the condition of the high ξ ; $\xi=3.0, 5.0$ and $10.0\ \text{v/v}\%$ and the small d_p ; $d_p=1.3, 1.5$ and $2.1\ \mu\text{m}$ are measured along the five z^* s in order to calculate $(1-\phi)$. Ψ is the ratio of $(1-\phi)$ at the downstream z_{n+1}^* to $(1-\phi)$ at the upstream z_n^* . The Φ is the ratio of $(1-\phi)_{\text{wall}}$ at the wall vicinity area to the ratio of $(1-\phi)_{\text{center}}$ at the center area at the same z^* . The Ψ_{center} at the center and Ψ_{wall} at the wall vicinity area is the ratio of $(1-\phi)$ between the downstream z_{n+1}^* to the upstream z_n^* with $n=1$ to 4 is numbering of the normalized stream cross-section position

2. Experiments

2.1 Experimental Set-up

The experimental set-up is composed of two syringe pumps, a micro channel, a capacitance measurement system and a computer as shown in Figure 1. The syringe pumps (IC3100 [KDS100], KD Scientific, USA; dimension: 23 x 15 x 12 cm with a minimum step rate is 1 step per 30 s) are used to control the flow rate within 60 mL into the two inlets of the micro channel. The Y-shape micro channel has two inlets, two outlets and has five cross-sections embedding multi layered electrodes. This micro channel embedded with a connector, sensor electrode and circuit board. The stable connection system is constructed in the micro channel in order to avoid the unstable measurement conditions between a micro channel electrode tail and a capacitance measurement system and to consider the noise effect. The connection system is comprised of spring pins, top and bottom circuit boards, pin connectors and a central board. The spring pin connects electrically the electrode tail and the circuit board. The top and bottom circuit boards are the planar electrode connector for sending data from spring pin to pin connector. The central board supports the micro channel and the circuit boards.

The capacitance measurement system is composed of a multiplexer (DAM200E) and a capacitance sensing unit (PTL 300E, ECT System). The capacitance sensing unit contains necessary AC bridge circuitry to measure the capacitance on the basis of the signals received from the micro channel electrode tails. The measurement signal is set to the ac voltage of 4.5 V at the frequency of $f=12.5$ MHz. Time required to take the one measurement between two unearthed electrodes is 25 μ s. We have employed 12 set of unearthed electrodes to measure the capacitance values in one cross-section resulting to 300 μ s for a complete set of measurement of a cross-section. Also, it is possible to measure the capacitance changes between two unearthed electrodes of the order of 0.01 fF in the presence of the stray capacitance to earth of 200 pF at a rate of 40,000 measurements per second [18]. Then, the measured capacitance data are fed to the computer.

Micro channel of the microfluidic device is used in this study to investigate the behaviour of particle migration. The detailed configuration of the micro channel used in this study is shown in Figure 2. Figure 2 (a) shows the three-dimensional view of the micro channel, (b) shows the cross-sectional view of the micro channel and (c) shows the micro computed tomography (CT) image of the diamond shape cross-sectional micro channel captured using a high speed micro CT machine (XT H 225, Nikon Technologies, Inc. Japan). The micro channel has two inlets with angle $\theta=30^\circ$ as shown in the left side of Figure 2 (a) for flow injection, and two outlets with angle $\theta=30^\circ$ as shown in the right side of Figure 2 (a) for flow discharge. There is a straight diamond-shaped section in micro channel with length of $z=20$ mm which is the main flow channel. This straight section of the micro channel has five cross-sections each separated by the distance of 5 mm. Each of these cross-sections has 12 multi layered electrodes. The cross-sectional dimensions i.e. the channel width is $D=700$ μ m. The origin of the coordinate system x , y and z is located at the center point of the diamond shape cross-section (x - y plane) and at the 8 mm distance (z direction) from the joint point of the two inlets. Each cross-section position is normalized with the total length of the straight channel; $z=20$ mm: $z_n^*=z_n/z$ where the first cross-section is located at the normalized stream cross-sectional position at $z_1^*=0$, the second cross-section is at $z_2^*=0.25$, the third cross-section is at $z_3^*=0.50$, the fourth cross-section at $z_4^*=0.75$ and the fifth cross-section is at $z_5^*=1.0$. The width of the electrode $w_e=75$ μ m and is along the y -axis and the length of the electrode is $l_e=200$ μ m along the x -axis. The electrode material is platinum and the substrate material is quartz glass. The length of the substrate embedded with the electrode in the cross-sectional micro channel $l_s=100$ μ m along the y -axis.

2.2 Experimental Methods and Conditions

The selected multi layered electrodes are connected as shows in Figure 2 (b) in order to measure the capacitances for the analysis of the particle migration. And, for the purpose of the discussion of the analysis, two areas are defined in the cross-section, viz.: the wall vicinity area and the center area. In the cross-sectional micro channel, the wall vicinity area and the center area are defined as locations of the cross-section for easy understanding of the behavior of the particle migration. For each defined area, the

capacitance C_{i-j} between two electrodes $i-j$ pair is measured at the five normalized stream cross-sectional position z_n^* with $n=1-5$. The measurements taken via electrode pairs 3-4 and 9-10 give the information of the wall vicinity area while the measurements taken via electrode pair 1-6 and 7-12 give the information of the center area. The distances between the electrodes 3 and 4 pair, l_{3-4} and between the electrodes 9 and 10 pair, l_{9-10} are 200 μm . While, the distances between the electrodes 1 and 6 pair, l_{1-6} and between the electrodes 7 and 12 pair, l_{7-12} are 600 μm .

The particles suspended in the deionized water flow are injected through the inlets with pressure difference driven by the syringe pump at the controlled flow rate $Q=4.9 \times 10^{-4} \text{ m}^3 \text{ s}^{-1}$. The mean flow velocity calculated from Q is $u=2.0 \times 10^{-3} \text{ ms}^{-1}$, corresponds to the Poiseuille flow region at the flow Reynolds number $\text{Re}=1000$ and the particle $\text{Re}_p=0.26$ in the case of the particle diameter $d_p=1.3 \mu\text{m}$, $\text{Re}_p=0.30$ in the case of $d_p=1.5 \mu\text{m}$ and $\text{Re}_p=0.42$ in the case of $d_p=2.1 \mu\text{m}$. The relative permittivity of the deionized water and the dielectric polystyrene particle are $\epsilon^{DWr}=15.0$ and $\epsilon^{Pr}=2.5$ respectively. The capacitances are measured between the electrode pairs at the wall vicinity area and center area under three initial particle concentrations ζ ; $\zeta=3.0, 5.0$ and $10.0 \text{ v/v } \%$ and three d_p ; $d_p=1.3, 1.5$ and $2.1 \mu\text{m}$ at the five normalized stream cross-sectional positions z_n^* ; $z_1^*=0, z_2^*=0.25, z_3^*=0.50, z_4^*=0.75$ and $z_5^*=1.0$.

Besides that, in the multi capacitance sensing, the dielectric particles subjected to the non-uniform electric field can experience dielectrophoretic (DEP) force as follows:

$$F_{DEP} = 2\pi \left(\frac{d_p}{2} \right)^3 \epsilon \text{Re}[K(\omega)] |\nabla| E|^2 \quad (1)$$

In equation (1), ϵ is a permittivity, $K(\omega)$ is Clausius Mossotti and E is an electric field. However, in this study the DEP generated at $E=4.5 \text{ V/mm}$ on $d_p=1.3, 1.5$ and $2.1 \mu\text{m}$ is sufficiently small, in the order of 10^{-9} as shows in Figure 3. Hence, the effect of the DEP force is neglected.

2.3 Multi Capacitance Sensing Method

During the calibration, the typical measurement sequence was started from the first excitation electrode $i=1$ to the detector electrode $j=2, 3, \dots, 12$ held at zero potential. The capacitance C_{i-j} between electrode i and j pair is measured and this procedure is continuously repeated at all electrode pairs. The reciprocity is valid i.e. $C_{i-j}=C_{j-i}$. The calibration was carried out by filling the micro channel first with deionized water ($\epsilon^{DWr}=15.0$). The capacitance thus measured is used to normalize the capacitance measured by filling the micro channel with the particles suspended in deionized water with initial particle concentration ζ . The absolute capacitances C_{i-j} between the electrodes $i-j$ pair is larger than the actual capacitance C_{i-j}^* because the stray capacitance C_{i-j}' is included as expressed by

$$\begin{aligned} C_{i-j}^{DW} &= C_{i-j}^{DW*} + C_{i-j}' \\ C_{i-j}^P &= C_{i-j}^{P*} + C_{i-j}' \end{aligned} \quad (2)$$

Where DW is for the deionized water under a static condition to eliminate the stray capacitance, P is particle measured under each flow condition, “*” represent the actual value and “'” is the stray effect. In this study, to remove the stray effect, the C_{i-j}' is cancelled by calculating the differential capacitance ΔC_{i-j} between C_{i-j}^{DW} and C_{i-j}^P as expressed by

$$\Delta C_{i-j} = C_{i-j}^{DW} - C_{i-j}^P = C_{i-j}^{DW*} - C_{i-j}^{P*} \quad (3)$$

From the capacitance, the permittivity between the electrodes $i-j$ pair of the particle measured under each flow condition ϵ_{i-j}^P is calculated by

$$\epsilon_{i-j}^P = \frac{\Delta C_{i-j} \times l_{i-j}}{A} \quad (4)$$

Where l_{i-j} is a distance between the electrodes $i-j$ pair and A is the area of electrode, $5.0 \times 10^{-12} \text{ m}^2$. From the permittivity, the normalized particle concentration between the electrodes $i-j$ pair $(1-\phi)_{i-j}$ under the particle flow condition is calculated by modified Maxwell equation [19] shown in equation (5).

$$(1-\phi)_{i-j} = \frac{\varepsilon_{i-j}^P - \varepsilon_{i-j}^{P0}}{\varepsilon_{i-j}^{DW} - \varepsilon_{i-j}^{P0}} \quad (5)$$

In equation (5) ε_{i-j}^{P0} is the permittivity between the electrodes $i-j$ pair for particle suspended in deionized water in the calibration condition under a static condition to eliminate the stray capacitance. From Equation (5), the averaged normalized particle concentrations at center area $(1-\phi)_{center}$ and at the wall vicinity area $(1-\phi)_{wall}$ are determined from the averaged $(1-\phi)_{i-j}$ of two electrode pairs as

$$(1-\phi)_{center} = \frac{(1-\phi)_{1-6} + (1-\phi)_{7-12}}{2} \quad (6a) \quad (1-\phi)_{wall} = \frac{(1-\phi)_{3-4} + (1-\phi)_{9-10}}{2} \quad (6b)$$

3. Experimental Results and Discussions

3.1 Normalized Particle Concentration

Figure 4 shows the normalized particle concentration $(1-\phi)$ obtained by Equations (6a) and (6b) under the three initial particle concentrations ζ at the center and the wall vicinity areas at the five normalized stream cross-sectional positions z_n^* in the case of particle diameter $d_p=2.1 \mu\text{m}$. The $(1-\phi)_{center}$ at the center area is decreased as the particles move along z^* irrespective of ζ while $(1-\phi)_{wall}$ at the wall vicinity area is increased. It reveals that the particles migrate from the center area towards the wall vicinity area as the particles move along z_n^* . So far, the relationship between $(1-\phi)$ and ζ is concerned, the $(1-\phi)_{center}$ at the center area is slightly decreased as ζ is increased irrespective of z^* while $(1-\phi)_{wall}$ at the wall vicinity area is slightly increased. For instance, quantitatively at z_5^* ; ($z_5^*=20 \text{ mm}$), $(1-\phi)_{center}$ in $\zeta=5.0 \text{ v/v } \%$ is decreased by 12.4% and $(1-\phi)_{center}$ in $\zeta=10.0 \text{ v/v } \%$ is decreased by 16.5% as compared with $(1-\phi)_{center}$ in $\zeta=3.0 \text{ v/v } \%$. On the other hand, at z_5^* ; ($z_5^*=20 \text{ mm}$), $(1-\phi)_{wall}$ in $\zeta=5.0 \text{ v/v } \%$ is increased by 5.0% and $(1-\phi)_{wall}$ in $\zeta=10.0 \text{ v/v } \%$ is increased by 7.0% as compared to $(1-\phi)_{wall}$ in $\zeta=3.0 \text{ v/v } \%$.

Figure 5 shows the $(1-\phi)$ obtained by Equations (6a) and (6b) under the three d_p at the center and wall vicinity areas at the five z^* s in the case of $\zeta=10.0 \text{ v/v } \%$. So far, the relationship between $(1-\phi)$ and d_p is concerned, the $(1-\phi)_{center}$ at the center area is slightly decreased as d_p is increased irrespective of z^* while $(1-\phi)_{wall}$ at the wall vicinity area is slightly increased. For instance, at z_5^* ; ($z_5^*=20 \text{ mm}$), $(1-\phi)_{center}$ in $d_p=1.5 \mu\text{m}$ is decreased by 12.0% and $(1-\phi)_{center}$ in $d_p=2.1 \mu\text{m}$ is decreased by 20.0% as compared to $(1-\phi)_{center}$ in $d_p=1.3 \mu\text{m}$. On the other hand, at z_5^* ; ($z_5^*=20 \text{ mm}$), $(1-\phi)_{wall}$ in $d_p=1.5 \mu\text{m}$ is increased by 4.0% and $(1-\phi)_{wall}$ in $d_p=2.1 \mu\text{m}$ is increased by 7.4% as compared to $(1-\phi)_{wall}$ in $d_p=1.3 \mu\text{m}$.

3.2 Particle Migration Ratios

From the result of the normalized particle concentration $(1-\phi)$ at the center and wall vicinity areas, we can predict particle migration along the micro channel flow. The experimental results show that the particle migration obviously occurred i.e. the particles moved from the center towards the wall vicinity area as the particles flow along the normalized stream cross-section position z^* . From the $(1-\phi)$, the relationship of the particle migration along the z^* and the relationship of the particle migration between two areas is determined. Two quantitative indicators are introduced to define the phenomenon of the particle migration.

3.2.1 Streamwise Migration Ratio

In order to investigate the tendency of particle migration in the transition of the downstream cross-section position, the streamwise migration ratio Ψ is introduced. Ψ is defined as the ratio of $(1-\phi)_{z_{n+1}^*}$ at

the downstream z_{n+1}^* to $(1-\phi)^{z_n^*}$ at the upstream z_n^* at the center and wall vicinity areas. Ψ is calculated by

$$\Psi_{center}^{z_n^* \text{ to } z_{n+1}^*} = \frac{(1-\phi)_{center}^{z_{n+1}^*}}{(1-\phi)_{center}^{z_n^*}} \quad (7a)$$

$$\Psi_{wall}^{z_n^* \text{ to } z_{n+1}^*} = \frac{(1-\phi)_{wall}^{z_{n+1}^*}}{(1-\phi)_{wall}^{z_n^*}} \quad (7b)$$

Figure 6 shows Ψ obtained by Equations (7a) and (7b) under the three initial particle concentrations ζ at the center and wall vicinity areas in the four transitions of z_n^* to z_{n+1}^* ($n=1-4$) in the case of particle diameter $d_p = 2.1 \mu\text{m}$. In this figure, $\Psi=1.0$ means that ratio of $(1-\phi)$ between the downstream z_{n+1}^* to the upstream z_n^* is the same and $\Psi>1.0$ means that the particles number is increased as the particles move along the downstream z_{n+1}^* . As shown in this figure, Ψ_{center} at the center area is decreased as the particles move along z_{n+1}^* irrespective of ζ while Ψ_{wall} at the wall vicinity area is increased.

So far, the relationship between Ψ and ζ is concerned, Ψ_{center} is decreased as ζ is increased irrespective of z_{n+1}^* while Ψ_{wall} is increased as ζ is increased. Quantitatively, at transition z_4^* to z_5^* ($z^*=15-20 \text{ mm}$), Ψ_{center} in $\zeta=5.0 \text{ v/v } \%$ is decreased by 1.7%, however Ψ_{center} in $\zeta=10.0 \text{ v/v } \%$ is increased by 6.5% as compared to Ψ_{center} in $\zeta=3.0 \text{ v/v } \%$. On the other hand, at z_5^* , Ψ_{wall} in $\zeta=5.0 \text{ v/v } \%$ is decreased by 3.2% and Ψ_{wall} in $\zeta=10.0 \text{ v/v } \%$ is decreased by 8.9% as compared to Ψ_{wall} in $\zeta=3.0 \text{ v/v } \%$. In the other hand, quantitatively, Ψ_{wall} at the transition of z_4^* to z_5^* ($z^*=15-20 \text{ mm}$) is increased by 1.23 times in $\zeta=3.0 \text{ v/v } \%$, 1.17 times in $\zeta=5.0 \text{ v/v } \%$ and 1.05 times in $\zeta=10.0 \text{ v/v } \%$ as compared to Ψ_{wall} at the transition of z_1^* to z_2^* ($z^*=0-5 \text{ mm}$). Also, it means that in the low ζ , the particles tend to concentrate on the center area as particles move from the upstream z_n^* to the downstream z_{n+1}^* while in high ζ , the particles tend to migrate towards the wall vicinity area. This result shows the relationship between Ψ and ζ where in the low ζ , the particle migration rate is adequately higher while the particle migration rate is moderate lower in the dense ζ as interaction between the particles becomes stronger which reduce the tendency of the particle migration in the channel flow. The big gap of Ψ means all the particles are moving as the particle flows through the downstream z_{n+1}^* . Highest ratio was observed at $\zeta=10.0 \text{ v/v } \%$ than in the lower ζ since the number of the particles in the high ζ is small and there is less interaction between the particles.

Figure 7 shows Ψ obtained by Equations (7a) and (7b) under the three d_p at the center and wall vicinity areas in the four transitions of z_n^* to z_{n+1}^* ; $n=1-4$ in the case of $\zeta=10.0 \text{ v/v } \%$. As shown in the figure, Ψ_{center} at the center area is decreased as the particles move along z_{n+1}^* irrespective of d_p while Ψ_{wall} at the wall vicinity area is increased. So far, the relationship between Ψ and d_p is concerned, Ψ_{center} is decreased as d_p is increased irrespective of z_{n+1}^* while Ψ_{wall} is increased as d_p is increased. Quantitatively, at transition z_4^* to z_5^* ($z^*=15-20 \text{ mm}$), Ψ_{center} in $d_p=1.5 \mu\text{m}$ is decreased by 8.0% and Ψ_{center} in $d_p=2.1 \mu\text{m}$ is decreased by 9.4% as compared with Ψ_{center} in $d_p=1.3 \mu\text{m}$. On the other hand, at transition z_4^* to z_5^* , Ψ_{wall} in both $d_p=1.5$ and $2.1 \mu\text{m}$ is decreased by less than 0.1% as compared with Ψ_{wall} in $d_p=1.3 \mu\text{m}$. From the quantitative calculation at $d_p=2.1 \mu\text{m}$, the decrement of Ψ_{center} at the center area is slightly higher than the increment of Ψ_{wall} at the wall vicinity area and vice versa. It means that the particles with small d_p tends to concentrate on the center area as the particles move from the upstream z_n^* to the downstream z_{n+1}^* while the large d_p particles tend to migrate towards the wall vicinity area.

As the particles move along the downstream z_{n+1}^* , the particles movement is depended on the inertial lift force acted on the particle in the flow. It has been clarified through a number of the previous experiments that the particle migration is strongly dependant on the d_p [7-8, 13-14, 16]. Although the ratio of d_p to the cross-sectional micro channel width in this study is too small with minor variance between d_p , the inertial particle migration occurs. It shows that the d_p plays an important role to determine the tendency of the particle migration even in the micro channel flow. In the case of the large d_p , the forces between the particles become strong which reduce the tendency of the particles to move actively in the streamline.

3.2.2 Cross-Sectional Migration Ratio

The other indicator is the cross-sectional migration ratio Φ which is defined as the ratio of the normalized particle concentration $(1-\phi)_{wall}$ at the wall vicinity area to $(1-\phi)_{center}$ at the center area at the same normalized stream cross-sectional positions z^* . The Φ is calculated by

$$\Phi = \frac{(1-\phi)_{wall}}{(1-\phi)_{center}} \quad (8)$$

This Φ indicates the tendency of the particles migration from the center area towards the wall vicinity area. Figure 8 shows the Φ under three initial particle concentrations ζ at each of z^* in the case of the particle diameter $d_p=2.1 \mu\text{m}$. In this figure, $\Phi=1.0$ means the $(1-\phi)_{wall}$ at the wall vicinity area is the same as $(1-\phi)_{center}$ at the center area and $\Phi>1.0$ means that the particle migration occurs from the center area towards the wall vicinity area. The Φ values of the every ζ conditions are exponentially increased as the particles move along the z_n^* . The $\Phi<1.0$, which means the particles tend to concentrate on the center area, is shown in the area from z_1^* to z_3^* ($z^*=0-15 \text{ mm}$), on the other hand, the $\Phi>1.0$ is shown in the area over z_4^* ; from z_4^* to z_5^* ($z^*=15-20 \text{ mm}$). Quantitatively, the Φ at z_4^* is increased by 2.14 times in $\zeta=3.0 \text{ v/v } \%$, 2.16 times in $\zeta=5.0 \text{ v/v } \%$ and 2.25 times in $\zeta=10.0 \text{ v/v } \%$ as compared to the Φ at z_3^* ($z^*=10 \text{ mm}$). It means that the particle migration from the center area towards the wall vicinity area strongly occurs over the halfway of the micro channel length; over z_3^* as the particles move along the z^* . In terms of the qualitative relationship between Φ and ζ , the Φ is slightly increased as ζ is increased. These results are similar to the particle migration behavior under the same condition of d_p and Reynolds number Re [15,20].

Figure 9 shows Φ under the three d_p at the five z^* s in the case of $\zeta=10.0 \text{ v/v } \%$. As shown in this figure, Φ is exponentially increased as the particles move along z^* irrespective of d_p . In terms of the qualitative relationship between Φ and d_p , the Φ is slightly increased as d_p is increased irrespective of z^* . Quantitatively, Φ at the z_4^* ($z^*=15 \text{ mm}$) is increased by 1.95 times in $d_p=1.3 \mu\text{m}$, 1.96 times in $d_p=1.5 \mu\text{m}$ and 2.05 times in $d_p=2.1 \mu\text{m}$ as compared to Φ at the z_3^* ($z^*=10 \text{ mm}$). It means that the particle migration strongly occurs in the large d_p because the large d_p induces sufficient lift force that contributes to the inertial particle migration due to the larger surface area than the smaller d_p . Besides, the large d_p is easier to move and migrate in the fluid flow due to the high surface area and the strong interaction between the particles. This result shows the dependency of the d_p on the particle migration where the particle migration slightly occurred from center towards the wall vicinity area.

In this study, the high ζ and the small d_p is employed to consider the effect of ζ and d_p on the particle migration in the micro channel. However, there is some limitation in order to determine the particle migration based on the experimental result. For instance, the electrode pair measurement area is including with the top, center and bottom edge of the cross-sectional micro channel area. Therefore, it is difficult to determine the absolute discussion for the center and wall vicinity area. However, in the present study, the particle migration is slightly occurred since the results show some difference between the center and the wall vicinity area. Besides, from the results of Ψ and Φ , various behavior's of the particle migration are observed even at the small d_p .

Conclusions

This study proposes two indicators to explain the phenomenon of the particle migration along the five normalized stream cross-sectional positions z^* in the micro channel. From the experimental results, the continuous particle migration is occurred in the high initial particle concentration ζ and small particle diameter d_p . We find the dependency of the particle migration in the high ζ while no significant different of the d_p effect. The details remarks are shows as follows:-

1. The normalized particle concentration $(1-\phi)_{wall}$ at the wall vicinity area is increased as the particles move along five z^* as the ζ is increased and as the d_p is increased. However, $(1-\phi)_{center}$ at the center area is decreased. It shows that the particles tend to migrate from the center area towards the wall vicinity area as the particles moved along five z^* s.

2. The streamwise migration ratio Ψ_{center} at the center area is decreased as the particles move along z^* irrespective of ζ and d_p while Ψ_{wall} at the wall vicinity area is increased.
3. The cross-sectional migration ratio Φ is exponentially increased as ζ and d_p is increased; especially, $\Phi > 1.0$ is observed over the halfway of the micro channel length; over z_3^* .
4. From the results of Ψ and Φ , the particle migration occurs from the center towards the wall vicinity area as the particles move along the z^* . In the case of low ζ and the small d_p , the particles tend to concentrate on the center area while in the high ζ and the large d_p , the particles tend to migrate towards the wall vicinity area. As the result, $(1-\phi)_{center}$ of the lower ζ and the smaller d_p is larger than $(1-\phi)_{center}$ of the higher ζ and the larger d_p .

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Figures

Figure 1 Experimental set-up

(a) Three-dimensional view (b) Cross-sectional view (c) Micro CT image
Figure 2 Micro channel embedding multi layered electrodes

Figure 3 Dielectrophoretic force of particle diameters $d_p=1.3$, 1.5 and 2.1 μm at $E=4.5$ V/mm

Figure 4 Normalized particle concentration under three initial particle concentrations ξ at the center and wall vicinity areas at the five normalized stream cross-sectional positions z_n^* s in the case of particle diameter $d_p=2.1$ μm

Figure 5 Normalized particle concentration under three particle diameters d_p at the center and wall vicinity areas at five normalized stream cross-sectional positions z_n^* s in the case of initial particle concentration $\xi=10.0$ vol%

Figure 6 Streamwise migration ratio under three initial particle concentrations ξ at the center and wall vicinity areas in four transitions of the normalized stream cross-sectional positions z_n^* to z_{n+1}^* in the case of particle diameter $d_p=2.1 \mu\text{m}$

Figure 7 Streamwise migration ratio under three particle diameters d_p at the center and wall vicinity areas in four transitions of the normalized stream cross-sectional positions z_n^* to z_{n+1}^* in the case of initial particle concentration $\zeta=10.0$ vol%

Figure 8 Cross-sectional migration ratio under three initial particle concentrations ζ at the five normalized stream cross-sectional positions z^* s in the case of particle diameter $d_p=2.1\mu m$

Figure 9 Cross-sectional migration ratio under three particle diameters d_p at the five normalized stream cross-sectional positions z^* s in the case of initial particle concentration $\zeta=10.0$ vol%