Evaluation of Particle Motion Characteristics in Microchannel Flow Alignment System with Ladder-type Electrodes

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Keywords: Microchannel flows, Particle motion control, Ladder-type electrodes, Dielectrophoretic force, Particle alignment

1. Introduction

Controlling the velocity, interval and timing of cells and particles in microchannel flows is an important issue to develop a high-throughput sensing and sorting system in lab-on-a-chip and micro-total-analysis-systems[1]. We have developed a technique that can control the particle velocity, interval between each particle and the exact timing of particles crossing a certain location in the channel by applying dielectrophoretic (DEP) force to the particles periodically with time and space using ladder-type electrodes[2].

The motion characteristics of the particle in the ladder-type electrode region and principle of the alignment mechanism, however, have not yet been fully evaluated and discussed. In this paper, position and velocity of the particles in the ladder-type electrode region were measured and compared with the period when the voltage (force) was applied to the particles to evaluate the phase difference between the particle relative position and the time when the force is exerted on the particles. We will then show how the phase difference contributes to the acceleration/deceleration of particles and convergence of the particle velocity, relative position and timing to the equivalent state. Finally, accuracy of controlling these particle characteristics are evaluated.

2. Experimental Methods and Conditions

Figure 1 shows the schematic of the electrodes and microchannel used in this study. Rail-shaped electrodes and ladder-shaped electrodes are attached to the bottom wall. Another electrode is attached to the top wall covering the overall area of the channel. AC voltage is supplied to the electrodes generating the electric field and DEP force. In the rail-type electrode region, DEP force is exerted on the particles in the height and spanwise directions and make them focus at the centerline of the electrodes near the channel bottom wall. In the ladder-type electrode region, area in which the DEP force accelerate and decelerate the particles in the streamwise direction are periodically located in the streamwise direction. Particles are aligned in the streamwise direction by periodically turning the supplied voltage on and off. If the on/off frequency is defined as $f_{\mathrm{on-off}}$ and the pitch of the periodic area for particle acceleration and deceleration as L_{pitch}, then the average particle velocity in equivalent state will be $u_{\mathrm{p,0}}=L_{\mathrm{pitch}}\cdot f_{\mathrm{on-off}}$.

The microchannel is composed of the channel made of SU-8 (MicroChem Co.) layer glass substrate on which Pt electrodes were patterned.

The channel width and height were 70μm and 54μm, respectively. Sheath-flow was generated by the three inlets of the microchannel. Polystyrene micro-particles 12μm in diameter (Thermoscientific Co., 4212A) were supplied from the center inlet and guided to the rail-type electrode region. Aqueous solution with 0.1wt% sodium lauryl sulfate (SLS) was used as working fluid. The cross-sectional average velocity of the flow was set as u_{m}=9.26mm/s. The applied voltage was $V_{\mathrm{P-P}}$=20V with frequency of f_{V}=10MHz. Voltage was turned on and off with frequency of $f_{\mathrm{on-off}}$=125Hz.

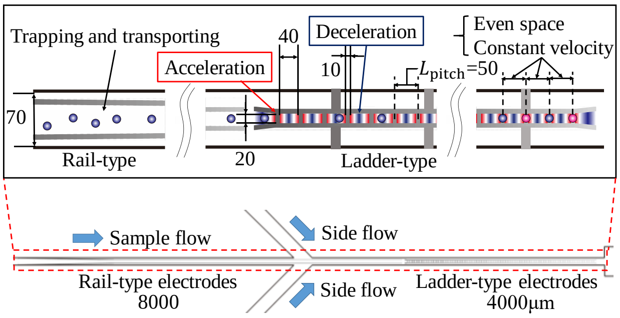

Figure 1. *Schematic of microchannel and electrodes.*

The position and velocity of the particles were measured using high speed video camera. The starting time of the frame recording was synchronized with the on / off phase of the applied voltage. Particle motion tracking software Cosmos Move-tr/2D (Library Co.) was used for particles motion analysis.

3. Results and Discussion

3.1 Particle Motion and Alignment Characteristics

We measured the particle position and velocity from the leading edge of the ladder-type electrodes and evaluated the particle motion converging to the controlling value (equilibrium state). Figure 2 (a) shows the relationship between particle velocity u_{p} and particle position x_{p}. Figure 2 (b) shows the phase difference θ of the particle position from their equilibrium position. Figure 2 (c) shows $\hat{u}_{\mathrm{p}}$ distribution in relation to the number of periodic region of the ladder-type electrodes. $\hat{u}_{\mathrm{p}}$ is the particle velocity averaged in one periodic region. The equilibrium position is where the total work done on the particle by the exerted forces in one periodic region is W=0[2].

The horizontal line shown in the graphs of Fig. 2 represents the value when particle is in equilibrium position: $\hat{u}_{\mathrm{p}}=L_{\mathrm{pitch}}\cdot f_{\mathrm{on-off}}$=6.25mm/s and θ=0. In Fig.2 (a), gray area represents the location of electrodes and red hatching area shows the period in which DEP force is applied.

In Figs. 2 (a) and (c), u_{p} and $\hat{u}_{\mathrm{p}}$ of different particles initially show different value with each other and from the equilibrium one. These velocities converges to an identical one at the same position and time as the particles flow downstream. This shows that the particles flow in the exact same trajectory with the same time profile.

Thus, the particles whose positions and velocities varies in the upstream region will align in ladder-type electrodes.

Fig. 2 (b) shows the phase difference θ for the particle depicted by the square symbols shown in Fig.2 (c). θ decreases as the particle flow downstream. In the region of i=10 and 19, θ shifts to the next periodic phase. $\hat{u}_\mathrm{p}$ also decreases as the particle flow downstream. Thus, a positive correlation is obtained between $\partial\hat{u}_\mathrm{p}/\partial i$ and $\partial\theta/\partial i$ which leads to θ converging to zero and $\hat{u}_\mathrm{p}$ to the velocity of equilibrium state. It should be noted that a sharp increase of $\hat{u}_\mathrm{p}$ is observed in the region of i=11. This is due to the fact that SiO_2 coating on the wiring area was partially damaged and removed so that electric field and resulting DEP force was generated.

3.2 Evaluation of Alignment Performance

We measured the particle velocity and timing in the downstream region of ladder-type electrodes to evaluate the performance of particle alignment. Timing represents the time when the particle passes through a certain position in the ladder-type electrode region. Δu_p represents the deviation from the velocity of equilibrium value of $u_{\mathrm{p},0}$, and Δt is the time deviation from the value of kt_s which is integer multiple of t_s which is the time when the particle passes through one periodic area. Figs. 3 (a) and (b) show the probability density distributions of $\Delta u_\mathrm{p}/u_{\mathrm{p,o}}$ at the inlet and outlet of the ladder-type electrodes, respectively. Figs. 3 (c) and (d) show the probability density distributions of $\Delta t/t_\mathrm{s}$. In the figures, $\Delta u_\mathrm{p}/u_{\mathrm{p,o}}$ and $\Delta t/t_\mathrm{s}$ distributes uniformly at the inlet. However, their distributions show the maximum value with a value of zero. The variation is approximately ±5%, which shows the accuracy of the particles velocity and timing control of the present method.

4. Conclusions and Future Works

We studied the characteristics of controlling the velocity, interval and timing of particles in microchannel flows using the ladder-type electrodes. A positive correlation between average velocity of each periodic unit of $\partial\hat{u}_\mathrm{p}/\partial i$ and $\partial\theta/\partial i$ was confirmed as $\hat{u}_\mathrm{p}$ decreased with θ. Alignment performance and accuracy was confirmed by evaluating the deviation of velocity from equilibrium state Δu_p and time deviation from the time when the particle passes through a specific location Δt in downstream region of ladder-type electrodes.

As a future work, we need to increase the accuracy of distribution of dielectrophoretic force to enhance the particle alignment performance.

References

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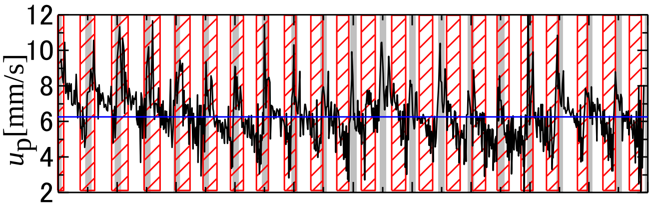
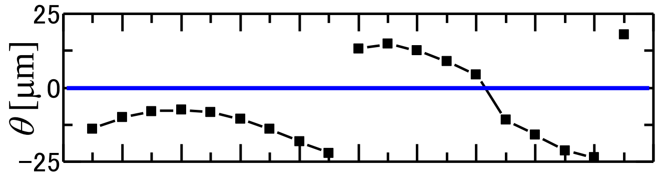
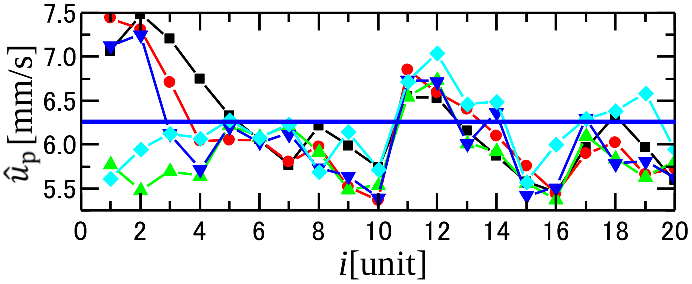


(a) Particle velocity u_p in each periodic unit. *Gray area represents the location of electrodes and red hatching area shows the period in which DEP force is applied.*

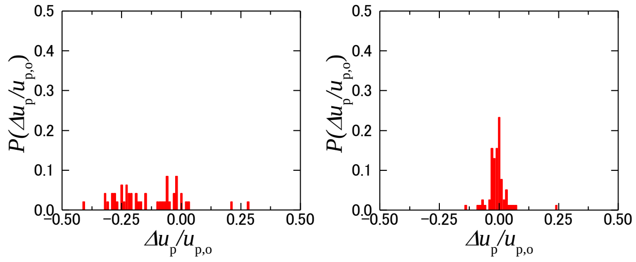


(b) *Phase difference* θ *in each periodic unit. The case corresponds to the line with square symbols in Fig. (c).*

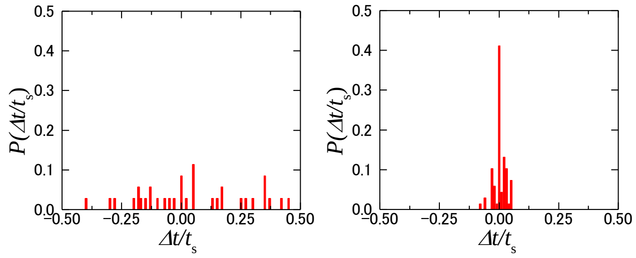


(c) *Average particle velocity in each periodic unit.*

Figure 2. *Phase difference* θ*, particle velocity* u_p*, and average velocity in each periodic unit* $\hat{u}_p$ *distributions in upstream region of ladder-type electrodes.*



(a) Inlet distributions (b) Outlet distributions



(c) Inlet distributions (d) Outlet distributions

Figure 3. *Probability density distributions of particles velocity shown in (a) and (b) and timing shown in (c) and (d) at inlet and outlet of ladder-type electrodes. PDF is for* Δu_p *(particle velocity deviation from the velocity of equilibrium value* $u_{p,o}$*) and* Δt *(time deviation from the value* t_s*).*