Numerical Simulation for Dielectrophoretic Separation of Micro-Particles in Moving Fluid and Electric Field

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Abstract — In this paper, the characteristic of the dielectric micro-particle motion is analyzed by solving the coupled problem of electromagnetic, fluidics and particle dynamics. The forces acting on micro-particles are obtained using the distributions of electric field and fluid velocity field, both of which are numerically calculated by the finite element method. The force consists of dielectrophoretic(DEP) force and drag force; two forces are driving terms in the Newton's equation for the particle motion. We propose a numerical analysis procedure to solve the coupled problem. A separator of dielectric micro-particles is designed and the dynamic characteristic of the micro-particle motion is simulated. The simulation results validated the proposed numerical scheme to analyze the micro-particle dynamics and also showed usefulness of the designed particle separator.

I. Introduction

The electric force acting on dielectric material under non-uniform field is called dielectrophoretic(DEP) force. Recently, the dielectric micro-particles, motions of which are controlled by the DEP force, play an increasing role in various areas, ranging from biomedical field to engineering. For example, many biotechnology devices have been being developed to manipulate micro-particles such as red blood cells, DNA, viruses, marker particles, etc. [1]. Their primary functions are to trap, separate and screen some specific particles. Before such devices are fabricated, it is crucial to evaluate performance of designed devices since their fabrication is very costly and time-consuming.

Most of such devices use fluid and electric field to control the micro-particles. Thus, the micro-particles experience many forces such as electric force, fluidic force, gravity, buoyancy force. Among them, the dominant forces are the DEP force and the fluidic drag force. The DEP force is related to both dielectric material properties and non-uniform electric field, and the drag force is determined by fluid velocity. The gravity and the buoyancy force can be neglected because the particles exist in a colloidal state.

In this paper, we propose a numerical procedure to solve the coupled problem, and carry out simulation for the designed device considering both fluid and electric field, simultaneously. The dielectric micro-particles in fluids such as blood or water are controlled not only by fluid stream but also by electric force. That is, the motion of the particles is determined by the distributions of electric field and fluid velocity. The characteristic of the particle motion is a kind of coupled problem of electromagnetic, fluidics and particle dynamics.

For numerical calculation of the DEP force and the fluid drag force, the electric field is calculated using the finite element method for the electrostatics, and the fluid velocity field is calculated also using the finite element method for the potential flow. The two forces are summed to be a driving force of the Newton's equation to calculate the particle motion, and the Runge-Kutta method is used to numerically solve the coupled motional equation.

In the designed device, the micro-particles suspended in laminar flow experience positive or negative DEP force according to both its relative permittivity and electric field intensity. The movement characteristic of the micro-particles is analyzed using the proposed numerical analysis procedure. Simulation results show validity of the proposed method and feasibility of the designed device.

II. Modeling of Particle Motion

The force acting on dielectric material suspended in non-uniform electric field is generated by interaction of imposed field with induced dipole moment. The DEP force on the dielectric particle, which is lossless in DC electric field, can be obtained using the effective dipole moment [2]:

$$\mathbf{F_{DEP}} = 2\pi\varepsilon_1 R^3 K \nabla E_0^2 \qquad (1)$$

where ε_1, R, and E_0 are fluid permittivity, particle radius and applied electric field, respectively, and K, known as the Clausius-Mossotti(CM) factor, can be expressed as

$$K = \frac{\varepsilon_2 - \varepsilon_1}{\varepsilon_2 + 2\varepsilon_1} \qquad (2)$$

where ε_2 is particle permittivity. The CM factor provides a measure of the magnitude of the DEP force, and its sign determines whether the particle moves toward strong electric field intensity or not.

The moving particles suspended in fluid experience the drag force as follow:

$$\mathbf{F_D} = 6\pi\eta(\mathbf{u} - \mathbf{v})R \qquad (3)$$

where η, $\mathbf{u}$ and $\mathbf{v}$ are viscosity, fluid velocity and particle velocity, respectively. The drag force can be calculated by relative velocity between fluid and particle velocity.

To evaluate the movement characteristic of the particles, these two forces on the particles are substituted into Newton's motional equation:

$$\mathbf{F_{DEP}} + \mathbf{F_D} = m\frac{d\mathbf{v}}{dt} \qquad (4)$$

where m is particle mass. Equation (4) can be solved using Runge-kutta method.

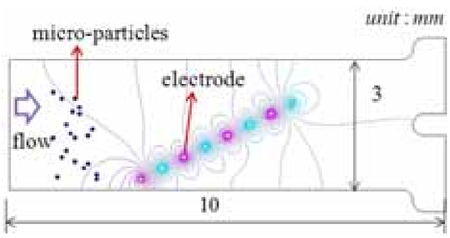
III. Numerical Analysis

A. Analysis Model

To obtain the reliable analysis results using well-known material property, the beads used in analysis are assumed as carbon particles instead of cells. The diameter of the micro-particles is 5 μm, and its mass density is assumed as 1.31 $g \cdot cm^{-3}$.

To design the device, The DEP force and the drag force are considered using three design variables. First, in material standpoint, analysis region is divided into two parts: fluid and micro-particles. The difference of permittivity between two materials effects on DEP force. Second, the drag force associated with the flow increases linearly with fluid velocity because the radius of the particles used in analysis is constant. Third, with considering breakdown of liquid(DI water), applied voltage value is chosen for preventing its malfunction.

In designed device, the distance between centers of the electrodes, of which diameter is 100 μm, is about 0.56 mm. When applied voltage is 1KV, maximum electric field intensity is 5.7MV/m which is about half of the breakdown field in DI water(13MV/m) [3]. Fluid field with flow velocity, $\mathbf{u} = 0.5$ cm/s, is laminar flow since Reynolds number of the device and the particles is much smaller than 0.2 [4]: $\mathrm{Re_d} \approx 1.5\times10^{-5}$ and $\mathrm{Re_p} \approx 5\times10^{-7}$.



(a) device size and equi-potential distribution

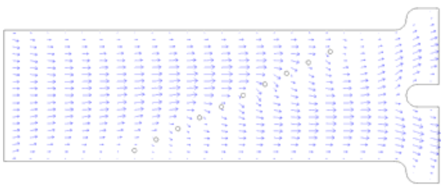
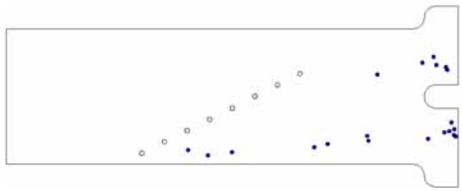

(b) flow velocity distribution

Fig. 1. Analysis model and field distributions

Fig. 1 shows the designed device to separate the micro-particles within fluid which are supplied through the inlet, and field distributions obtained by finite element method. Each force calculated from each field distribution is used to obtain the changing position of the particles by solving (4). For visualization of the micro-particles, the depicted ones are exaggerated due to micro size of the real particle, and the relative permittivity of fluid and the particles is 80 and 5, respectively.

B. Analysis Results

The analysis results are shown in Fig. 2. There are two types of movement characteristic as electric field exists or not. In Fig. 2.(a), all micro-particles move along with certain stream because electric field does not exist. When the voltage is applied, the micro-particles near each electrode are affected by negative DEP force, and it cannot go through the spaces between electrodes. As a result of this, all particles are gathered in upper channel. In other word, the dynamic characteristics of the micro-particles can be controlled by electric field.


(a) particle motion in only fluid

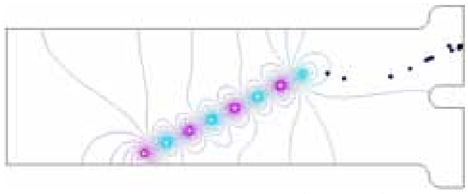

(b) particle motion in electric field and fluid

Fig. 2. Simulation results as electric field

IV. Conclusion

We have proposed the numerical procedure that can solve the coupled problem to analyze the particle movement in fluid and electric field. In the designed micro-particle separating device, the total force acting on the beads was calculated from each field distributions, and the dynamic characteristics were estimated by proposed algorithm. The simulation results showed that the micro-particles can be safely and rapidly manipulated using electric field, the usefulness of the proposed numerical scheme which can be applied to movement analysis of the dielectric micro-particle.

V. References

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