Myung Ki BAEK

NUMERICAL ANALYSIS OF DIELECTRIC MICRO-PARTICLE MOTION IN A FLUID AND ELECTRIC FIELD

ABSTRACT *We present numerical analysis of a coupled problem composed of fluidics, electromagnetic and particle dynamics. The forces acting on the dielectric micro-particle consist of a dielectrophoretic (DEP) force, drag force and gravitational force in the proposed analysis model. DEP force and drag force are calculated using the distribution of the electric field and fluid velocity field to analyze the characteristic of the micro-particle motion. The forces exerted by each field are driving terms in the Newton's equation for particle motion. The designed particle separating device, which has the one inlet and the two outlets, is simulated to validate proposed numerical scheme. The analysis results show the trace of the micro-particles can be analyzed using the proposed numerical approach.*

Keywords: *dielectric micro-particles, electric field particle separating, motion, fluid, dielectrophoretic force, drag force, gravitational force, Newton's equation, simulation, numerical approach.*

1. INTRODUCTION

The electric force acting on dielectric material under non-uniform electric field is called dielectrophoretic(DEP) force. Recently, dielectric micro-particles, whose motions are controlled by the DEP force, play an increasing role in various

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areas, ranging from environmental engineering to biomedical fields [1]. For example, minute particles caused during a manufacturing process have a detrimental influence on people’s health, and can damage modern equipment consisting of micro scale devices. These pollutants can be manipulated using the DEP force. Many particle control devices have been developed.

The dielectric micro-particles existing in the air experience many forces such as electric, drag, gravitational and buoyancy [2]. Among them, the dominant forces are electric force, drag force and gravity since buoyancy is very small relative to gravity. The electric force is related to both dielectric material properties and non-uniform electric field. Drag force is determined by fluid velocity. Last, gravity is associated with physical constants: volume, density and particle radius.

In this paper, we propose a numerical procedure to solve the coupled problem, and design a separating device. The micro-beads in air can be controlled by both fluid stream and electric force. That is, the motion of the particles is determined by the distributions of an electric field and fluid velocity. The characteristic of the particle motion is a form of coupled problem of electromagnetic, fluidics and particle dynamics [3].

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 to calculate numerically the DEP force and fluid drag force. The gravitational force can be obtained easily from material properties. The three forces are summed to be a driving force of Newton’s equation to calculate particle motion. The Runge-Kutta method is used to numerically solve the coupled motional equation.

The micro-particles suspended in laminar flow experience positive DEP force in the designed device based on their relative permittivity and electric field intensity. The movement characteristics of the micro-particles are analyzed using the proposed numerical analysis procedure. Simulation results show validity of the proposed method and feasibility of the designed device.

2. MODELING OF PARTICLE MOTION

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

$$\mathrm{p} = 4\pi\varepsilon_1 R^3 K \mathrm{E}_0 \tag{1}$$

where ε_1, R, and $\mathbf{E}_0$ are fluid permittivity, particle radius and applied electric field, respectively, and K, known as the Clausius-Mossotti (CM) factor, can be expressed as

$$K = \frac{\varepsilon_2 - \varepsilon_1}{\varepsilon_2 + 2\varepsilon_1} \tag{2}$$

where ε_2 is particle permittivity. Using the above equations, the well-known expression for the DEP force can be written as [4]:

$$\mathbf{F_{DEP}} = 2\pi\varepsilon_1 R^3 K \nabla E_0^2 \tag{3}$$

According to (2), the CM factor, whose value range is within $-0.5 \leq K \leq 1.0$, provides a measure of the magnitude of the DEP force and the particle's direction of motion. If fluid permittivity is larger than that of the particle, then it is called the negative DEP force due to the CM factor.

The moving particles suspended in fluid experience the drag force as follows [2]:

$$\mathbf{F_D} = 6\pi\eta\,(\mathbf{u} - \mathbf{v})R \tag{4}$$

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

These two forces on the particles are substituted into Newton's motional equation of motion to evaluate the movement characteristic of the particles:

$$\mathbf{F_{DEP}} + \mathbf{F_D} + \mathbf{F_G} = m\frac{dv}{dt} \tag{5}$$

where m is particle mass, $\mathbf{F_G}$ is gravity force. Equation (5) can be solved using the Runge- Kutta method.

3. ANALYSIS OF PARTICLE DYNAMICS

3.1 Analysis Model

The DEP force and the drag force are considered using, three design variables of the design of the device. First, from the material standpoint, the analysis region is divided into two parts: fluid and micro-particles. The difference of permittivity between the two materials affects the DEP force. Second, the drag force associated with the flow increases linearly with the fluid velocity because the radius of the particles used in analysis is constant. Third, the applied voltage value is chosen to prevent its malfunction considering breakdown of air.

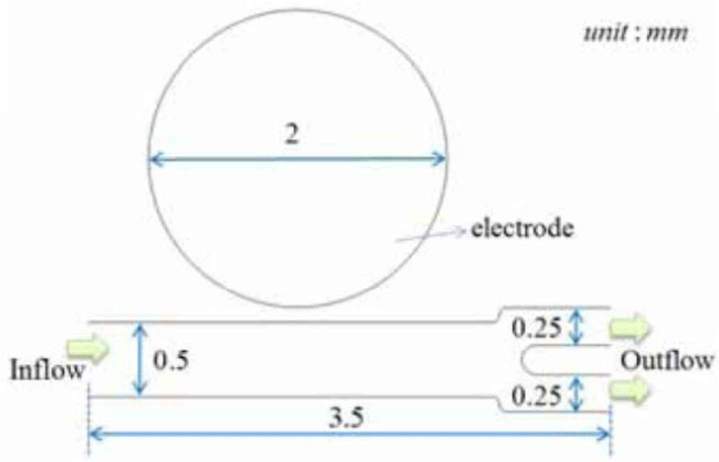

Fig. 1. Analysis model

Figure 1 shows the designed device. It consists of the one elect-rode and the channel. The electro-de, whose diameter is 2 mm, keeps 0.1 mm away from the channel. The maximum electric field intensity is about 2.4 MV/m when the applied voltage is 5.5 kV. This is under the breakdown field in the air. The channel has one inlet and two outlets, and the micro beads are supplied with fluid velocity through the inlet. The fluid field with flow velocity, $\mathbf{u}$ = 0.5 cm/s, is a laminar flow, since the Reynolds number of the device and the particles is much less than 2000 and 1 [5]: $\mathrm{Re_d} \approx 0.16$ and $\mathrm{Re_p} \approx 1.7\times10^{-3}$.

3.2 Numerical Model

The drag force and DEP force can be calculated from each field distribution. Figure 2 shows the fluid velocity field distribution obtained by the finite element method. The drag force can be obtained from equation (4) using the relative velocity between fluid and the particles at each point.

All particles experience the DEP force when the voltage is applied. Figure 3(a) shows equipotential distribution, and Figure 3(b) depicts the gravitational force and the DEP force on the line that is near the bottom of the channel in Figure 3(a). The DEP force between 0.3 mm and 2.6 mm is stronger than the gravitational force, which is about 0.8×10^{-12}[N], and the CM factor is a positive value. Therefore, in this region all particles move towards the electrode.

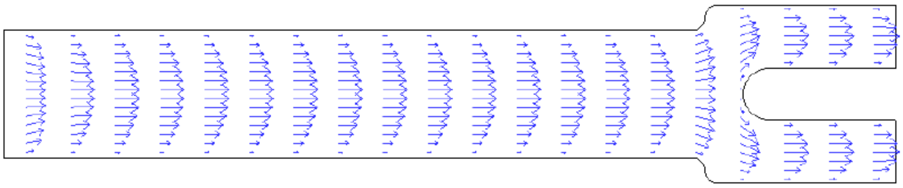

Fig. 2. Flow velocity distribution

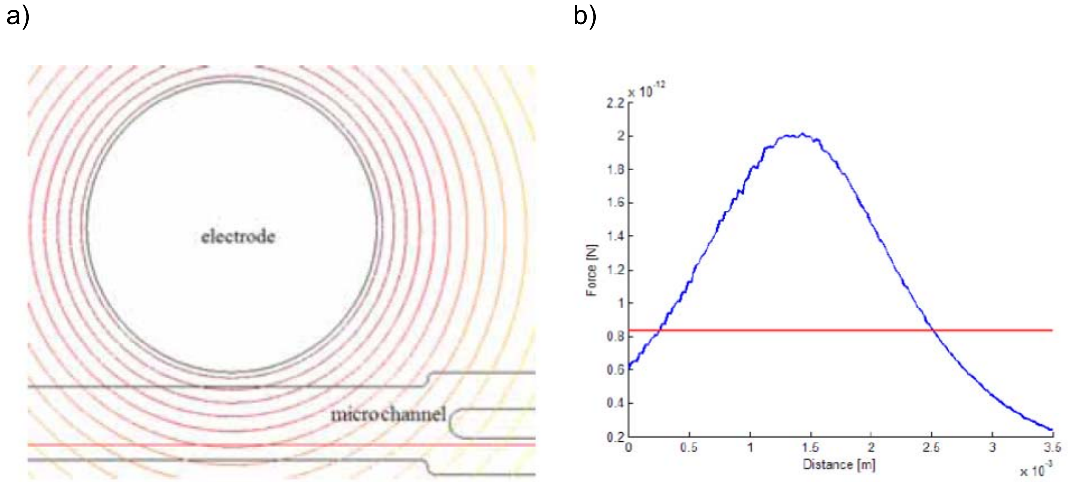

Fig. 3. Comparing the forces near the bottom of the channel:
a) equi-potential line distribution; b) DEP force and gravity force

The applied voltage to generate the same electric field becomes lower, as the electrode diameter becomes smaller. However, the DEP force acting on the particles at the same distance is weak in the case of a smaller electrode, because it is proportional to the electric field gradient. Figure 4 shows the analytical result of the quarter of the electrode in Figure 3. The region where the DEP force is dominant is smaller than the one of the bigger electrode model.

The beads used in analysis are assumed to be carbon particles, instead of cells, to obtain the reliable analytical results using well-known material property. The diameter of the microparticles is 5 μm, and its mass density is assumed as 1.31 $\text{g}\cdot\text{cm}^{-3}$. Figure 5 shows the particle motion in the electric field only.

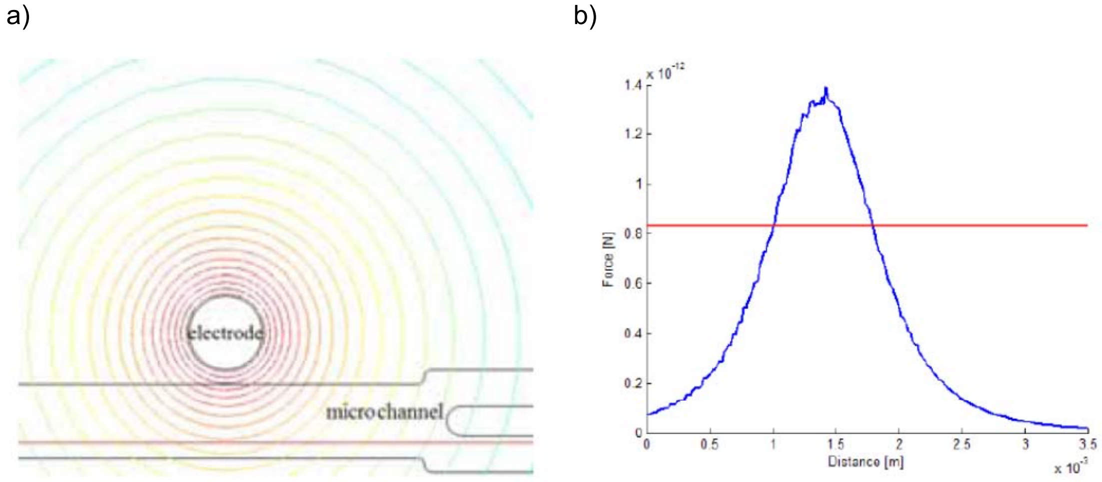

Fig. 4. Comparing the forces near the bottom of the channel:
a) equi-potential line distribution; b) DEP force and gravity force

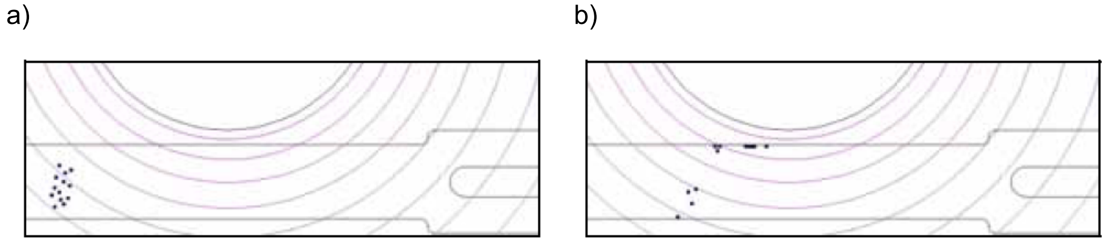

Fig. 5. Electric field only exists:
a) Initial particle position; b) Particle motion under electric field

Figure 6 shows the simulation results. The carbon micro-particles are supplied from the right side, and it can be manipulated by electric field. The injected beads move toward the lower channel when there is no electric field, since the forces acting on them are the drag and the gravitational forces. In contrast, if the voltage is applied, then all particles gather in the upper channel due to the DEP force.

4. CONCLUSION

We have proposed a numerical procedure that can solve the coupled problem to analyze the particle movement in fluid and electric fields. The total force acting on the beads was calculated from each field distributions by the finite element method, because the forces vary with its position. These values are substituted in Newton's equation to calculate the particle motion. The Run-

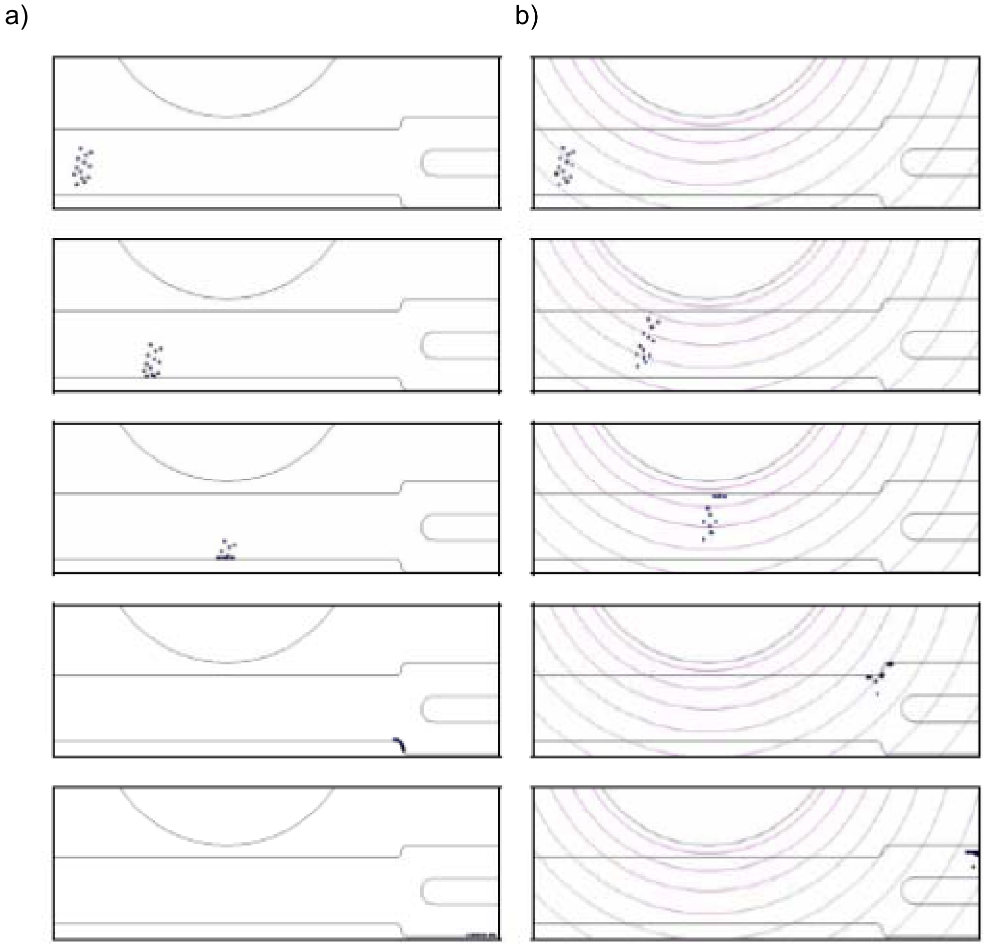

Fig. 6. The micro-particle motion:
a) Turned off the electrode; b) Turned on the electrode

ge-Kutta method is used to solve the coupled motional equation. The dynamic characteristics were estimated using the proposed algorithm in the micro-particle separating device designed.

Fluid velocity, material properties of a particle and the applied voltage are considered in order to design the separating device. The simulations showed that the particles can be safely and rapidly manipulated using the DEP force, which is proportional to both the CM factor and electric field gradient. The usefulness of the proposed numerical scheme is validated.

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NUMERYCZNA ANALIZA RUCHU MIKROCZĄSTEK DIELEKTRYCZNYCH W CIECZY I W POLU ELEKTRYCZNYM

Myung Ki BAEK

STRESZCZENIE *Artykuł przedstawia numeryczną analizę problemu, na który składają się strumienniki, pole elektromagnetyczne i dynamika cząstek. W modelu proponowanej analizy, na mikrocząstki działają siły dielektroforetyczne (DEP), siły oporu i siły grawitacyjne. Siły oporu i siły DEP są obliczane z rozkładu pola elektrycznego i pola prędkości cieczy w celu analizowania charakterystyki ruchu mikrocząstek. Siły wywierane przez każde z tych pól stanowią wyrazy napędu w równaniu Newtona dla ruchu cząstek. Projektowane urządzenie do separacji cząstek, które ma jedno wejście i dwa wyjścia, jest symulowane w celu sprawdzenia proponowanego schematu numerycznego. Wyniki analizy wykazują, że trajektorie mikrocząstek można analizować, stosując proponowane podejście numeryczne.*