Simulation of the Electrical Response of Charged Particles in the Fluid for Horizontal Switching Electrophoretic Cell

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Abstract

Electrophoretic displays (EPDs) are attracting considerable attentions as a paper-like display. Especially, Electrophoretic cell consists of micron-sized, charged particles dispersed in a viscous fluid. When an external electric field is applied, the charged particles move with a speed proportional to the particle mobility and the local field strength. In electrophoretic displays fast switching times are required, so knowing the particle mobility is very important. In this paper, we study a novel simulation for calculating the particle motions submerged in a viscous fluid for horizontal switching electrophoretic cell.

1. Introduction

Electrophoretic displays are reflective displays based on the movement of charged particles in a fluid [1,2]. Liquid suspensions containing particles are quite importance in science and industry. To advance the applications of charged particle control technology, it is important to investigate the behavior of the particles by an external electric field. Investigation of the charged particle mobility under the electric or other kinds of body forces is a key issue among researchers in this area. There have been several numerical studies was in progress. In the previous paper, the new simulation method was presented by Tanaka and Araki. They assumed that the solid is considered to be one kind of fluids. And also, the solid has much higher viscosity than the fluid [3]. Using Tanaka's method, Kodama analyzed the dynamical behavior of the particle in the fluid but he assumed that the charged colloid consists of the non-

electrostatic body force and the attached ions [4]. In EPDs application, however, it is important property for prediction about electrophoretic mobility. Thus, we apply the electrostatic body force our numerical method. Especially, the intensity of applied voltage on the electrode can be a key factor to control the switching velocity. The calculation of the behavior of a charged particle in the fluid system may be not easy because of the complex dynamic couplings between electrophoretic motion and the hydrodynamic behavior.

2. Potential calculation of EPDs cell

The liquid is placed between the two glasses. In our simulation, conductive electrode coated fluid/bottom glass layer surface. The glasses are separated by a spacer of typically $40 \mu m$ thickness. Figure 1 shows the simply geometry in our simulation.
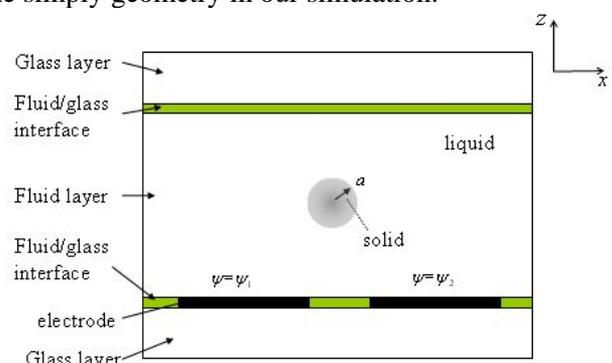

Fig. 1. The cell geometry used for calculation.

2. Potential distribution of EPDs cell structure

To obtain the potential distribution of the fluid layer and glass layer, we solve the Maxwell's equation (eq. (1)). Equation (1) can be solved directly since it is a linear equation.

$$0 = div(\varepsilon_0 \varepsilon \, grad \; \psi) \tag{1}$$

where ε is the dielectric constant of the medium and ε_0 is the permittivity of vacuum and ψ denote the electrostatic potential. We can take advantage of the over relaxation method as follows.

$$\psi_{i,j} = \widehat{\psi}_{i,j} + \omega(\psi_{i,j} - \widehat{\psi}_{i,j}) \tag{2}$$

where ω is an over-relaxation constant. For the most efficient calculation, optimum value for ω depending on the grid system. In our calculation, we select the optimum value $\omega = 1.95$. Here the hat variables denote the obtained in the previous time step. We will use these as superscripts to the variables to denote evaluation of the variables at the corresponding points.

Especially, in glass layer which is homogeneous and isotropic. To obtain potential distribution of the fluid layer and glass layer, we calculate electric potential by solving eq. (1) using a successive over-relaxation (SOR) method. Calculation in the fluid/glass interface, however, we have to artificial boundary condition for electric potential.

From the Gauss law $divD = \rho$, the normal components of D must be continuous fluid/glass interface layer if there is no surface charge. The z components of D in the fluid and the glass can be express as follow.

$$D_z^{fluid} = -\varepsilon_0 \left(\varepsilon_{fluid} \frac{\partial \psi}{\partial z} \right) \tag{3}$$

$$D_z^{glass} = -\varepsilon_0 \left(\varepsilon_{glass} \frac{\partial \psi}{\partial z} \right) \tag{4}$$

where ε_{fluid} is the dielectric constant of the fluid, and ε_{glass} is the dielectric constant of the glass. At the interface between fluid layer and glass layer, D should satisfy as $D_z^{fluid} = D_z^{glass}$. We employed above scheme for our calculation. We calculate the potential distribution of EPDs cell structure for solving electrophoretic mobility equation. When a voltage is applied in one direction, the charged particle moves towards the opposite electric polarity electrode.

Figure 2 shows the simulation result solving external electric field applied on bottom electrode within a rectangular cavity filled incompressible fluid.
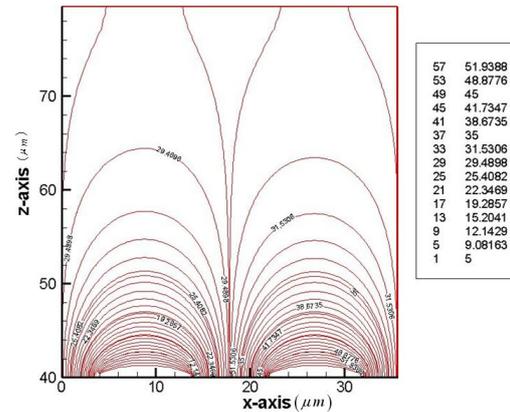

Fig. 2. Simulation result of potential distribution of fluid layer using SOR method. The applied voltage is 60V on right electrode. The curves represent equal electric potential curves.

When a voltage of the opposite sign is applied, the particle position was switching.

3. Governing equation

Adopting a continuum assumption, the Navier-Stokes equations modified to include the body force term which related with external electric field. The governing equations can be calculate the electrophoretic flow by solving the continuity equation coupling with momentum equation, which are given respectively, by

$$\nabla \cdot V = 0 \tag{5}$$

$$\rho(\frac{\partial}{\partial t} + V \cdot \nabla)V = -\nabla p + \nabla \cdot \mu[(\nabla V) + (\nabla V)^T] \\ + \rho_e E \tag{6}$$

where ρ is the fluid density and V indicate velocity vector comprising u (x-direction) and v (z-direction) in Cartesian coordinates, p is the static pressure, μ is the fluid viscosity, ρ_e is the net electric charge density and E is the electric field. Here the third term stems from the body force term which explained to electrostatic interaction and the external field.

According to electrostatics theory, the potential is governed by the Poisson equation, i.e.

$$\nabla^2 \psi = -\frac{\rho_e}{\varepsilon \varepsilon_0} \tag{7}$$

The continuous force field F acting on a charged particle can be calculated by follow equation.

$$F = \sum_i \frac{F_{i,j} \phi_{i,j}}{\int \phi_{i,j} dr} \tag{8}$$

To calculate velocity of particle, we can take electrophoretic mobility equation:

$$u_{ep} = \rho_e / 6\mu_f \pi r \tag{9}$$

where r is the Stokes' radius of the particle [5]. The Stokes radius can also be equated to the mass of the particle by the following equation:

$$Mass = (4/3)\pi r^3 V_{ps} \tag{10}$$

where V_{ps} is the partial specific volume of the solute.

We consider in a 2-D space within a rectangular cavity filled incompressible fluid with the homogenous charge distribution spherical particle with radius a. We calculated a phase function to obtain difference value for express the solid phase as follow.

$$\cdot \phi_{i,j} = 0.5 \left[1 + \tanh \frac{a - \sqrt{(x_{i,j} - x_p)^2 + (y_{i,j} - y_p)^2}}{\xi} \right] \tag{11}$$

where ξ is the interface width, (x_p, y_p) are the coordinates of the solid particle's center position. So, we can see that at the point within the point of the particle center. The value of ϕ in a computational domain is given as the volume fraction. The phase function is close to 1 for solid and far from the particle it is zero for the liquid. Tanaka assumed that the solid is also considered as a kind of fluid like the surrounding medium [3]. The fundamental difference of the materials is given from difference in the viscosity. We let the viscosity of the particle μ_p. Then, the viscosity ratio $\mu_p = \mu_p / \mu_f$ is assumed to be very large in principle so that the solid is hardly deformable.

In addition, we also consider a specific body force about electrophoretic mobility.

Using the phase function, we can describe difference in a viscosity. In the above eq. (6), we assumed that the materials are given from difference in the viscosity. The viscosity of solid particle is higher than the fluid. The viscosity μ is determined solely from the following equation.

$$\mu = \mu_p + (\mu_p - \mu_f)\phi \tag{12}$$

Here μ_f is the viscosity of fluid. When an electric field is applied to a horizontal switching electrophoretic cell, the field would cause particle motion or charge redistribution around the particle. A charged particle would be move to the electrode carrying charges with opposite electric polarity in a viscous fluid. The interfacial forces such as the pressure and the fluid's shear forces are automatically considered and thus we do not need to calculate these forces separately. The only thing we should do is to integrate the equation of motion given in terms of the coordinates of the particle's center position:

$$x_p = \hat{x}_p + \Delta t \, u_p, \, y_p = \hat{y}_p + \Delta t \, v_p \tag{13}$$

where the velocity components of the particle center can be obtained from

$$u_p = \frac{\int u \, \phi \, dxdy}{\int \phi \, dxdy} \cong \frac{\sum_{i,j} u_{i,j}^p \, \phi_{i,j}^p}{\sum_{i,j} \phi_{i,j}^p} \tag{14}$$

3. Results and discussion

In the above eq. (6), we assume that the density of solid particle is the same as that of a liquid. Thus, ρ is a constant in space. And also, we set the second term of lhs to be zero (Stokes approximation). This is justified since the Reynolds number is quite small for aqueous suspensions of colloids of sub-micron size [3]. In our simulation, the drift motion of a particle is much faster than the diffusional motion. Thus, there are no random Brownian motions of particles for simplicity. We only take the electrostatic force into account. We calculate movement of a charged particle which fixed above the right electrode of the coordinate system: see Fig.3(a) and Fig.4(a). We imposed applied voltage on left electrode. At the fluid layer surface, the no-slip boundary condition is employed meaning $V = 0$, left and right side employed periodic boundary condition. We calculate

time evolution by using an explicit Euler integration. The simulation parameters are shown as table 1.

particle radius (a)	$2\ \mu m$
charge density of particle (ρ_e)	$-10\ \mu C/g$
viscosity of dispersant fluid(oil) (μ_f)	$10cs$
Dielectric constant of the fluid(oil) (ε_f)	2.6
Permittivity of vacuum (ε_0)	$8.8542 \times 10^{-12} F/m$
Reynolds number (Re)	1
Interface width (ξ)	0.1
Cell gab	$40\ \mu m$
Width of the electrode line	$10\ \mu m$
Distance between bottom two electrode	$8\ \mu m$

TABLE 1. The values of model parameters.

The negative charged particle mobility is numerically studied according to setup the system in terms of intensity of applied voltage for the electrophoretic flow. Fig. 3 shows a calculation result that switching time of the particle center's position move toward the bottom electrode with opposite electric polarity.
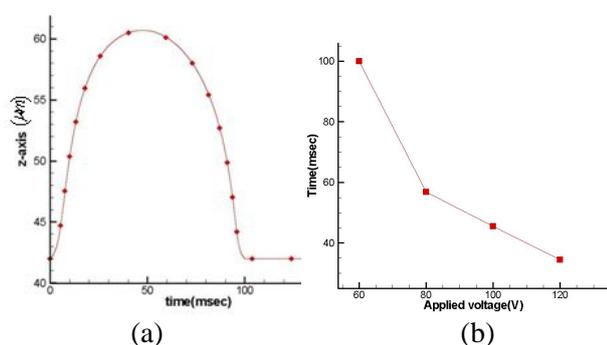

(a)	(b)

Fig. 3. The calculate result of simulation: (a) the line denotes moving patch of the particle when applied voltage is 60V and (b) result of switching time according to change of applied voltage.
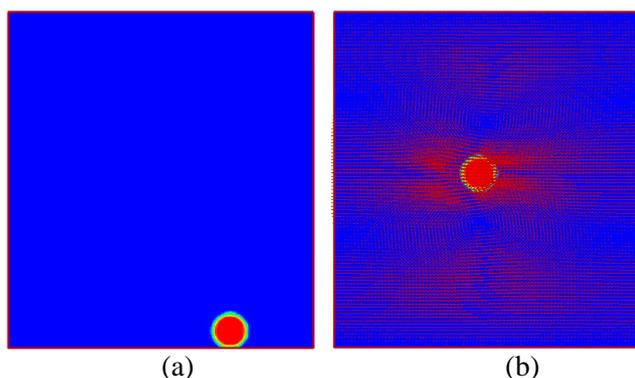

(a)	(b)

(c)

Fig. 4. Snapshots of electrophoretic property in micro channel flow. The allow denotes the velocity field in the fluid layer. (a) 0ms, (b) 47.3ms, (c) 99.91ms.

4. Summary

In this paper, we demonstrate electrophoretic mobility according in intensity of applied voltage. We give results of simulations of how the charged particle move inside a pixel and how this movement leads to the velocity field distribution. And also, we calculated the electrokinetic force and the hydrodynamic behavior. As a result, this method can be applied to electrophoretic deposition of problems in charged particle interaction.

5. Acknowledgements

5. References

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