

P.12: Numerical Calculation of Dynamical Behavior of Charged Particles in the Fluid for Horizontal Switching Electrophoretic Cell

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Abstract

This paper calculates the dynamical behavior of a circular cylinder share charged particle in a viscous fluid for horizontal switching electrophoretic cell. Electrophoretic displays (EPD) 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

In the past few years, many techniques have been developed to realize an electric paper [1,2], including electrophoretic display, electrochromic display, liquid crystal reflective display, electrochromic, Gyricon, and others [3-5]. Among them, particle-based techniques have been long developed for their high contrast and low power consumptions. There have been presented that a comprehensive study of the AC and DC electrokinetic properties of submicrometer latex particles as a function of particle size and suspending medium conductivity and viscosity is presented in 2005 [6]. In most particle-based displays, such as electric paper, charged particles are used and driven by DC field. To advance the applications of charged particle control technology, it is important to investigate the behavior of the particles in an electric force field. Prediction of the motion of particles surrounded by a viscous fluid under the electric or other kinds of body forces is a key issue among researchers in this area. In the previous paper, Bert et al. have studied the transport of particles in electrophoretic display using analytical formulae [7]. They presented complete model for the internal particle distribution of electrophoretic image displays. From this model, simulation formulas for electrical and optical properties are calculated. The group of Tanaka and Araki proposed a new simulation method for colloidal suspensions. The key assumption in the Tanaka's method is that the solid is also considered as a kind of fluid like the surrounding medium [8]. 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 [9]. In colloidal suspensions for display application, however, we normally apply the electrostatic body force for controlling the

switching behavior of the particle. Especially, the total charge of the particle in the fluid can be a key factor to control the switching velocity.

2. Theory

2.1. Electric potential calculation for horizontal switching electrophoretic cell

A typical case is a electrophoretic cell consisting of two flat and infinitely large glass plates whose surface are coated with conductive electrode. Real cells used for EPDs, however, have a two- or three-dimensional (2-D or 3-D) structure because of the existence of patterned electrodes that generate nonuniform fields. In this paper, we discuss numerical methods for calculating the electrohydrodynamical characteristics in 2-D cell, including the relaxation method for the hydrodynamic calculation, the artificial boundary condition for electric potential and the fluid/glass interface. Figure 1 shows the cell geometry used for calculation.

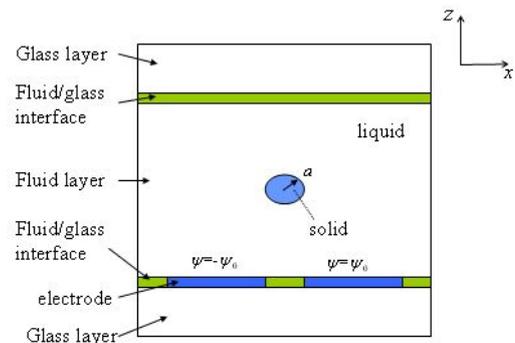


Figure 1. Geometry of the cell structure for calculation of electrophoretic display.

A charged particle would be attracted toward the electrode carrying charges with opposite electric polarity in a viscous fluid. In order to calculate the electrohydrodynamic behavior of the particle, we take into account potential distribution to specific model flow.

2.1.1. Electric potential calculation inside the fluid layer and glass layer

By solving eq. (1), we can obtain the potential distribution of the fluid layer and glass layer. Note that eq. (1) is Maxwell's equation

(the Gauss law). Equation (1) can be solved directly since it is a linear equation.

$$0 = \text{div}(\varepsilon_0 \varepsilon \text{grad } \psi) \quad (1)$$

where ε is the dielectric constant of the medium and ε_0 is the permittivity of vacuum. We also denote the electrostatic potential as ψ . We will use these as superscripts to the variables to denote evaluation of the variables at the corresponding points. We can take advantage of the over relaxation method as follows.

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

where ω is an over-relaxation constant. There is an optimum value for ω , for the most efficient calculation, depending on the grid system (number of grids). In our calculation, the optimum value of ω was about 1.95. Here the hat variables indicate the ones obtained in the previous time step.

Alternatively, in glass layer which is homogeneous and isotropic, we calculate electric potential by solving eq. (1) using a successive over-relaxation (SOR) method.

The calculation inside the fluid layer and glass layer is straightforward, but we have to be careful about the calculation the fluid/glass interface layer and the boundary condition for electric potential.

2.1.2. Electric potential calculation for the fluid/glass interface layer

From the eq. (1), Gauss law $\text{div}D = \rho$, 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 are as follow.

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

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

where $\varepsilon_{\text{fluid}}$ is the dielectric constant of the fluid, and $\varepsilon_{\text{glass}}$ is the dielectric constant of the glass. At the interface between fluid layer and glass layer, the z components of D in the fluid and the glass are same ($D_z^{\text{fluid}} = D_z^{\text{glass}}$). We employed above scheme for our calculation. We can obtain potential distribution of EPDs cell for coupling with hydrodynamic equation. Figure 2 show calculated results of the potential distribution of the fluid layer within a rectangular cavity filled incompressible fluid in horizontal switching electrophoretic cell.

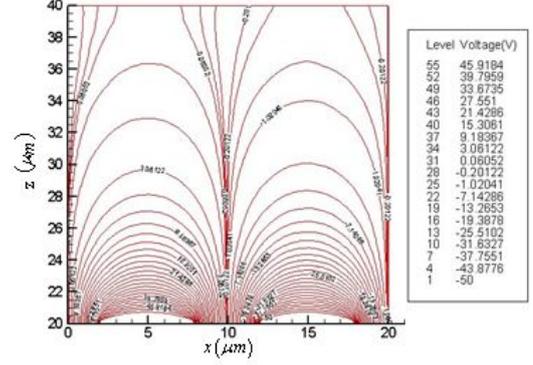


Figure 2. Calculated potential distribution of fluid layer of horizontal switching cell using SOR method based on Poisson equation. The curves represent equal electric potential curves.

2.2. Governing equation

For the simplicity of the explanation, we consider a specific model problem defined by simple geometries. We consider in this respect a two-dimensional space within a rectangular cavity filled with an incompressible fluid with density ρ_f and viscosity μ_f .

We also consider a solid particle of a circular cylinder share with radius a submerged in the viscous fluid; see figure 1. The key assumption in the Tanaka's method is that the solid is also considered as a kind of fluid like the surrounding medium [8]. The fundamental difference of the two phases of the materials is given from difference in the viscosity. More specifically, the solid particle is provided with a high 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. We also consider a specific body force. We can consider arbitrary body forces, but in this paper we only take the electrostatic force into account as shown in fig. 2

Adopting a continuum assumption, electrophoretic flow can be modeled by the Navier-Stokes equations modified to include the body force term generated by external electric field. The governing equations of the electrophoretic flow are the continuity and momentum equation, which are given respectively, by

$$\nabla \cdot \mathbf{V} = 0 \quad (5)$$

and

$$\rho \left(\frac{\partial}{\partial t} + \mathbf{V} \cdot \nabla \right) \mathbf{V} = -\nabla p + \nabla \cdot \mu \left[(\nabla \mathbf{V}) + (\nabla \mathbf{V})^T \right] + \mathbf{F} \quad (6)$$

where \mathbf{V} donates velocity vector comprising u (x -direction) and v (z -direction) in Cartesian coordinates, p is the static pressure, ρ is the fluid density, μ is the fluid viscosity. Here the third term stems from the body force term. It can be explain by follow equation.

$$\mathbf{F} = \rho_e \mathbf{E} \quad (7)$$

where ρ_e is the net electric charge density and \mathbf{E} is the electric field. Eq. (7) explained to electrostatic interaction and the external field.

According to electrostatics theory, the potential is governed by the

Poisson equation, i.e.

$$\nabla^2 \psi = -\frac{\rho_e}{\epsilon \epsilon_0} \quad (8)$$

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

$$F = \sum_i \frac{F_{i,j} \phi_{i,j}}{\int \phi_{i,j} dr} \quad (9)$$

2.2.1. Phase field function

The solid particle is provided with a high viscosity. And also, we calculate the hydrodynamic behavior and the electrophoretic force on the charged particles surrounded by a viscous fluid in the horizontal switching cell. We consider in a 2-D space within a rectangular cavity filled incompressible fluid with the homogenous charge distribution spherical particle of a circular cylinder shape with radius $a = 1 \mu m$. For the phase function, we use the value calculated from the following equation depending on the position of the point of the particle r_p .

$$\phi_{i,j} = 0.5 \left[1 + \tanh \frac{a - \sqrt{(x_{i,j} - x_p)^2 + (y_{i,j} - y_p)^2}}{\xi} \right] \quad (10)$$

Where (x_p, y_p) are the coordinates of the solid particle's and ξ controls the interface width. So, we can see that at the point within the particle centered at r_p . The phase function is close to 1 and far from the particle it is zero. Within this approach, discretization of the governing equation is usually done by the Finite Volume method. Then the value of ϕ in a computational cell is given as the volume fraction of the dispersed phase in this cell. Hence the phase boundary is implicitly given by the values of the scalar field of ϕ values throughout the domain. The viscosity μ is determined solely from the following equation.

$$\mu = \mu_f + (\mu_p - \mu_f) \phi \quad (11)$$

Here μ_p is the viscosity inside the particle. It should be noted that the fluid particle approximation becomes exact in the limit of $\mu_p / \mu_f \rightarrow \infty$ and $\xi / a \rightarrow 0$. The viscosity of the fluid particle is set to be $\mu_p = 20 \mu_f$. Using the phase function, 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. When an electric field is applied to a horizontal switching electrophoretic cell, the field would cause particle motion or charge redistribution around the particle. Since the solid particle is of a circular shape we are allowed it use a very simple method to obtain the particle's position. 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:

$$x_p = \hat{x}_p + \Delta t u_p, \quad y_p = \hat{y}_p + \Delta t v_p \quad (12)$$

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

$$u_p = \frac{\int u \phi dx dy}{\int \phi dx dy} \cong \frac{\sum_{i,j} u_{i,j}^p \phi_{i,j}^p}{\sum_{i,j} \phi_{i,j}^p} \quad (13)$$

Then, we calculate the effect of various parameters associated with EPD.

3. Results and discussion

3.1. Setup of the system

A spherical particle of radius a is fixed with its center located at the origin of the coordinate system. At infinity, an external field is imposed two pattern of bottom electrode. At the fluid layer surface, the no-slip boundary condition is employed meaning $V = 0$. Note that the drift motion of a particle in our simulation is much faster than the diffusional motion. Thus, there are no random Brownian motions of particles in our simulation for simplicity. In the above eq. (6), we assume that the density of solid particle is the same as that of a liquid, namely, 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 [8]. When, in electrophoretic flow, strongly external electric field applied EPDs cell, particle mobility depending on charge density of charged particle. We calculate time evolution by using an explicit Euler integration for eq. (6).

| | |
|---|--------------------------------|
| particle radius (a) | 1 μm |
| charge density of particle (ρ_e) | -10 $\mu C / g$ |
| viscosity of dispersant fluid (μ_f) | 1 cP |
| Dielectric constant of the fluid (ϵ_f) | 80 |
| Permittivity of vacuum (ϵ_0) | 8.8542 $\times 10^{-12} F / m$ |
| Reynolds number (Re) | 1 |
| Interface width (ξ) | 0.1 |
| Cell gap | 20 μm |
| Width of the electrode line | 6 μm |
| Distance between bottom two electrode | 4 μm |

Table 1 The values of the model parameters.

3.2. Particle size effects

The effects of particle size in the electric potential distribution are first considered. Because, the velocity of particle is related to the external electric field with the amount of particle's charged. . When an external electric field is applied, the charged particles move with a speed proportional to the particle mobility and the local field strength. Fig. 2 shows calculated results of the potential distribution of the fluid layer and Fig.4 shows a charge density inside the charged particle.

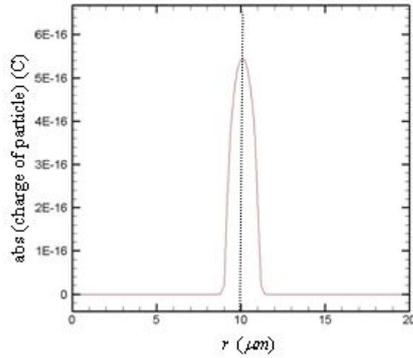


Figure 4. The charge of the cylinder particle of radius $a = 1\mu\text{m}$ on simulation domain.

3.3. External electric field strength effect

The dependence of flow rate on external electric field strength for the electrophoretic flow is also numerically studied according to setup of the system. Fig. 5 shows a calculation result that switching time of the particle center's position move toward the bottom electrode with opposite electric polarity. From about $z=21.5$ its speed decreases so rapidly due to the bottom's retarding effect.

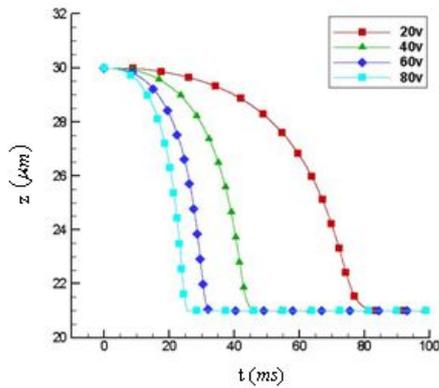


Figure 5. Calculated potential distribution in the fluid payer of the horizontal switching cell.

We investigated the motion of the charged particle with its initial position in 2-D space. A charged particle clearly shows electrophoretic behavior that it is attracted toward the electrode carrying charges with opposite electric polarity. Fig. 6 shows a snapshots of the process of electrophoretic deposition of single charged particle.

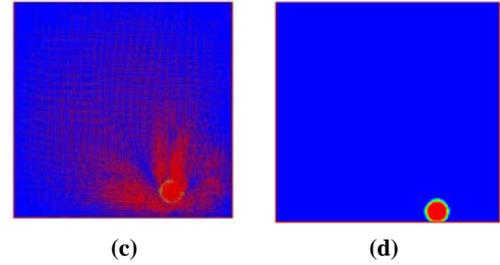
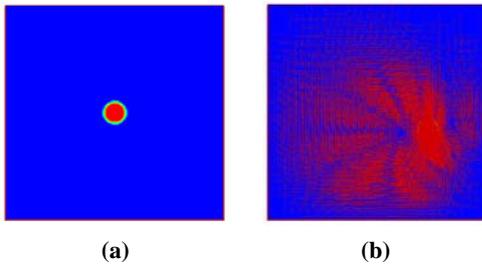


Figure 6. The density plot represents the phase separation between the fluid and the particle. The arrows in the figure indicate the velocity field in the cell. The applied voltage ψ_0 is 60 V and time at (a) 0 ms, (b) 20 ms, (c) 30 ms, (d) 60 ms.

4. Conclusions

In this paper, we demonstrate that by driving them by applying an external field we may perform surface-sensitive particle separation, using the dependence of particle motion on electrophoretic properties. We confirmed that the mobility is almost independent of external electric field. As a result, this method can be applied to electrophoretic deposition of problems in charged particle interaction.

5. Acknowledgements

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6. References

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