Analysis of Particle Movement by Dielectrophoretic Force for Reflective Electronic Display

Han-Lim Kang, Chul Am Kim, Sang-Il Lee, Yong-Kwan Shin, Yun-Hi Lee, Young-Cho Kim, and Byeong-Kwon Ju

***Abstract*—We analyze the movement of particles in an electric paper that consists of upper and lower electrodes. Particles inserted in a fluid move under the influence of an electric field when voltage is applied to the electrodes. The movement of particles is determined by the intensity of the electric field, the viscosity of the fluid, and the q/m of the particles. Each factor has an impact on the independent particles. Considering these factors, we analyze the characteristics of the particles' movements. We analyze the behavior of the electric paper with experiments based on Stokes' Law.**

***Index Terms*—Electric field, electric paper, reflective electric display.**

I. INTRODUCTION

DURING the last several decades, researchers developed flat-panel displays using different technologies such as the plasma display panel (PDP), liquid crystal display (LCD), organic light-emitting diode (OLED), and electronic paper display (EPD) [1]–[11]. Flat displays have attracted attention due to their conformable and flexible properties [12]. Among the driving techniques, EPD devices have many features that are not satisfied by a light-emitting display, including excellent readability, low driving power, good memory effect, and flexibility [13]–[15]. These features are associated with the EPD's simple structure and the motion of its charged particles [16]. Reflective electronic displays use charged particles. However, particles in a fluid are attracted to each other, and moving particles influence the movement of trailing particles and make them trace the route that was originally traveled. Moving particle groups create another electric field, which influences the movement of other particles by attracting or repelling them [17]–[20]. Therefore, charged particles exhibit irregular movements that lead to degradation in the electrical and optical properties of a display that has a short life span [21]. In other words, the motion of a particle is an important factor in defining the physical characteristics of an EPD. In this study, we will express the movement mechanism of particles by using equations, and prove those mechanisms by experimenting with the hypothesis that movement of particles in fluids affected by the electric field and fluid resistance.

II. BASIC CONCEPT

An electric paper display panel is defined by particle movements in the fluid. The movement mechanism of particles in fluid is expressed by an equation based on Stokes' law [22]. Stokes' law is written as

$$F_d = 6\pi\mu V d \tag{1}$$

where F_d is the drag force of the fluid on a sphere, μ is the fluid viscosity, V is the velocity of the sphere relative to the fluid, and d is the diameter of the sphere. Using this equation, we can express the mechanism of particle motion in fluid. When an electric field is applied to the electrodes, there are two basic mechanisms for movement: particles in fluid are affected by the electric field and by the resistance of fluid. Here, we substitute the variable $6\pi\mu d$ for b, and it therefore becomes $F_d = bV$.

This is shown in the following equation:

$$\vec{f} = q\vec{E} - b\vec{v} = \mathrm{m}\frac{d\vec{v}}{d\vec{t}} \tag{2}$$

The interaction force and van der Waals force are ignored in the present study. Using the electric field theory, the kinetic theory, and Stokes' law, equations were derived for the kinetic energy among particles. The first term of equation (2) is due to the electric field; that is, the particle was affected by the E-field, and the second term is due to the resistance of the fluid and the viscosity, q is the amount of electric charge of particles, b is the coefficient of friction, and $\vec{v}$ is the velocity of the particles. We rearrange the equation to make v the subject, as follows:

$$v_i = \frac{qE_i}{b_i}\left(1 \pm e^{-\frac{b_i}{m}t}\right) \tag{3}$$

Here, q is the electric charge of the particles, m is the mass of particles, and b_i is the resistance of the fluid. The velocity of particles in fluid is proportional to the electric charge of the particles and electric field, while it is inversely proportional to the

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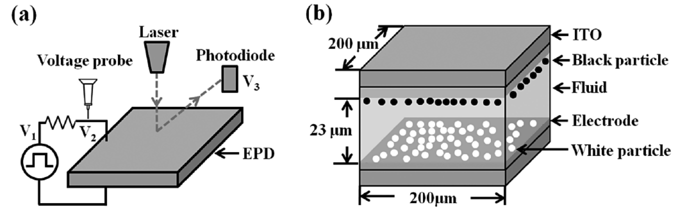

Fig. 1. (a) Measurement system of the response time and the electrical characteristics. The size of the panel is 3 cm × 3 cm. The input voltage is V_1, the measurement voltage is V_2, and the intensity of the reflected incident light is measured by V_3. (b) Schematic of an EPD made with the ITO glass. The size of the cell is 200 μm × 200 μm, and the cell gap with a plaid pattern between each piece of ITO glass is 23 μm. There are 12 769 cells in one panel and a plaid pattern in each ITO glass.

resistance of the fluid. Equation (3) shows that the characteristics of electric paper are similar to those of a capacitor. The term $(e^{-b_i/mt})$ is similar to the RC time constant. The velocity of particles increases or decreases, showing a positive nonlinear relationship, and the velocity gradient is influenced by the mass of particles and the coefficient of friction. If particles in the panel are affected by different masses of electric charges and coefficients of friction, particles can rise with the influence of the electric field. z indicates the height of the rising, and can be obtained by an integral counting method, as follows:

$$z = \left(\frac{q_+ E_i}{b_i^+} + \frac{q_- E_i}{b_i^-}\right)\left(\frac{m^+}{b_i^+} - \frac{m^-}{b_i^-}\right) \tag{4}$$

z increases proportionally to the electric charge and the mass of the particles, while it is inversely proportional to the resistance of the fluid. Since the sizes and mass of black and white particles are different, the particles determine the electric charges of each particle and are accordingly affected by different resistances of fluid. This shows that each particle is supposed to move a certain distance in the fluid. By using equations (3) and (4), we can express, in a simple manner, the movement of the particles with regard to the reflectivity of particles and the response time.

III. EXPERIMENT

We adopted a dual-particle system where the panel of electronic paper consists of an upper and lower ITO glass layer, and the fluid between the ITO glasses. After injecting the panel with the electronic ink, which is mixed with fluid and particles, the panel is packed with silicon.

Fig. 1(b). is a schematic of an EPD. Particles are fabricated through PMMA, and the average sizes of the white and black particles are 350 nm and 100 nm, respectively. The fabrication process of the electrophoretic particles makes the white particle positively charged by the process involving the core-shell typed TiO_2-poly(MMA-co-acrylamide) composite nanoparticles, and the black particle is negatively charged by the process involving the core-shell typed carbon black-poly(MMA-co-acrylic acid) composite nanoparticles. The direction of the electric field can determine the movement of both the positively and negatively charged particles. The electrophoretic medium is the mixture of a transparent isoparaffinic oil (Isopar-G) and fluorohydrocarbon solvent (halocarbon oil), and its viscosity is 3 cP. White and black suspensions were mixed with a mass ratio of 10:1, and particles with a mass ratio of 1:1 were inserted into the fluid [23], [24].

The methyl methacrylate(MMA) is a hydrophobic material that enables good dispersion of particles in oil. The acrylamide is a unimolecular material for which the electron count is low. On the contrary, acrylic acid is an electron-rich unimolecular material. Because ions are not created in non-polar mediums, positive and negative charges are not induced. Consequently, the electron-rich material induces a negative charge, and the electron-poor material induces a positive charge.

The status of particles dispersed by the medial mill method is good for operate EPD. Therefore, there is a low degree of viscosity. In addition, the stability of a particle in solution depends on the conditions being optimal. However, particles dispersed by the medial mill method were slowly deposited at the bottom over time. However, occasional stirring or shaking causes it to return to the original state. On the contrary, the stability of particles increases with time.

The force of attraction affects particles having opposite charges. However, the particles were not dispersed in polarity medium such as water, but the particles were dispersed in a low degree of ionization oil. Therefore, there were low forces of attraction between particles having opposite charges. When we proceeded with the process of particle dispersion, both white and black particles were distributed. Therefore, the dispersion forces of the particles are much stronger than their attractive forces.

Fig. 1(a). shows the measurement system of the response time We applied a bias voltage of a pulse wave to the panel. Using an oscilloscope with a resistance of 800 Ω, we measured the applied voltage of the power supply (V_1) and the applied voltage to the panel (V_2). The reflectivity (V_3) was measured by detecting the particles that had moved in the photodiode. All experiments were conducted in a dark room.

Fig. 2(a) shows the results of measuring the applied voltage of the power supply and the voltage wave applied to both ends. The stabilizing time of the applied voltage to the panel (V_2) is 1.5 ms. The stabilizing time is included within capacitor characteristic, discharge ratio of fluid, and a current contributions of particle. This tells us that the characteristics of the panel are the same as those of a capacitor.

Fig. 2(b) shows the results of measuring the reflectivity of particles. We can have more accurate results from the slope of this graph (V_3) which measures the response time of a particle. The movement time of white particles is indicated by the rising time, and the movement time of black particles is indicated by the falling time. When we apply this to equation (3), we determine that the movement time of the particles is proportional to a logarithmic function of time. White particles and black particles of non-uniform sizes stacked up in the panel. The particles experience uniform acceleration in the electric field. At this time, the different sizes and masses of black and white particles determine the different velocities. The particles arrived different time at top electrode, thus the graph being log function form by time. The rising time of V_3 ranges from hundreds of milliseconds to a few seconds, while the falling time is hundreds of milliseconds. In other words, the electric capacity determines the minimum response time of the particles.

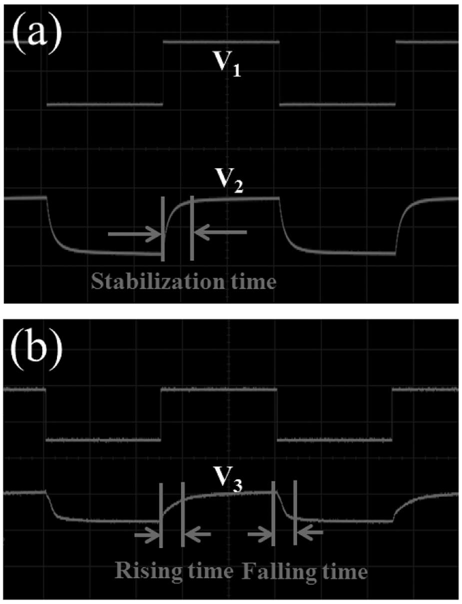

Fig. 2. (a) Results of the applied voltage of the power supply (V_1) and the applied voltage to the panel (V_2). (b) Results of measuring the reflectivity of particles driven by the applied voltage. The rising time of the particles is a few seconds, whereas the falling time of the particles is hundreds of milliseconds.

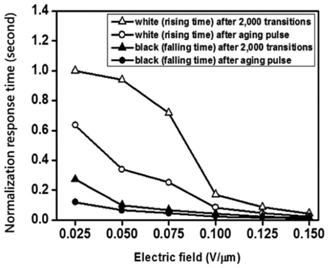

Fig. 3. Response time driven by the electric field of the panel, and the change in the response time according to the number of image transitions.

IV. RESULT AND DISCUSSION

The movement mechanism of particles is expressed in equations (3) and (4), and we confirmed that the motional characteristics of the particles mimic the influence of a capacitor. We measured the response time driven by the electric field of the panel, and the change in the response time according to the number of image transitions. We identified the impact on the response time and reflectivity that was caused by these variables.

Fig. 3. shows that an increase in the electric field applied to the panel leads to a decrease in the response time of the particles. We applied different levels of electric fields to the panel, from 0.025 V/μm to 0.15 V/μm. The applied electric field is 0.025 V/μm, and the breakdown electric field is 0.1 V/μm. After 2,000 transitions, the response time increased by 40–60%. We measured the response time of the particles with different levels of electric field from 0.025 V/μm to 0.15 V/μm in increments of 0.025 V/μm. Using the incident light of a laser that was reflected by the particles, we measured the current at the photodiode and normalized this value.

As shown in equation (2), we found that the electric field increases proportionately with the response velocity. The response time of the white particles decreases linearly when the electric field of the panel is in the range of 0.025 V/μm to 0.1 V/um. However, few changes are detected in an electric field of greater than 0.1 V/μm. The driving voltage of the white particles is 0.025 V/μm. The velocity of particles in the driving voltage is in the tens of μm/s. However, after 2,000 instances of movement, the response time of the particles decreased by approximately 40–60%. A particle-clumping phenomenon causes an increased mass of particles. Because of the crush and gravitation of particles in the panel, the particles clump. The result is that the particles have different charges. This can be explained by an increase in particle mass and a decrease of charged particles.

These changing factors induce a decrease in velocity, as shown in equation (3). However, after 2,000 instances of movement, the response time of a particle is not acceptable when the breakdown electric field is higher than 0.1 V/μm. In other words, we can identify that the charge and mass of a particle does not have a direct impact on the breakdown electric field. The rate of change of response time of black particles by increasing the electric field is less than it is increased for the white particles. The driving voltage of the black particles is 0.025 V/μm, and the breakdown electric field is 0.05 V/μm. After 2,000 instances of movement, the response time of the black particles increased by less than 10%.

The differences in response times between the black and white particles can be explained by the sizes of the two different particles. A black particle is one-third the size of a white particle. Because of this, a black particle moves in a relatively lower electric field than a white particle does. In the next experiment, we will check the correlation between the distance of movement of the particles and their reflectivity.

As the electric field increased, the reflectivity of the black particles was reduced, and few changes were detected with an electric field of lower than 0.02 V/μm. The reflectivity of particles in the panel is determined by the traveling distance between the electrodes of the panel. The changes in reflectivity, depending on the electric field, can be explained by the different sizes of particles. The size of a white particle ranges from 100 nm to 1 μm, and its average size is 350 nm. On the other hand, the size of a black particle ranges from 50 nm to 150 nm, and its average size is 100 nm. Different sizes of particles caused electric charges. In other words, the number of particles in the panel is proportional to the electric field.

Fig. 4(a)shows the measurement of the reflectivity of white and black particles. After 2,000 instances of movement, the reflectivity of the white particles decreased by 20%, while that of the black particles decreased by 10%. The contrast ratio of white and black particles decreased by 40%. After 2,000 instances of movement, few changes were detected in the reflectivity of the white particles in an electric field of higher than 0.05 V/μm. In addition, there were few changes in the reflectivity of the black particles with an electric field of higher than 0.02 V/μm. The driving voltage of the panel changed according to the times of movement.

As shown in Figs. 4(c) and (d), the particles were not entirely separated but were mixed together by fluid convection, which influenced the reflectivity. The black particles mixed with white

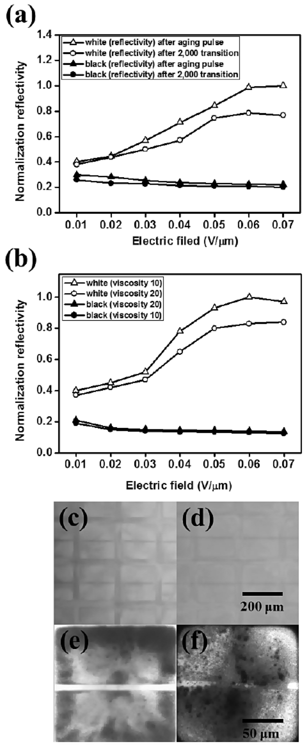

Fig. 4. (a) Measurement of the reflectivity of white and black particles driven by the electric field. After 2,000 instances of movement, the reflectivity and the contrast ratio have decreased. (b) Correlation between reflectivity and viscosity. (c), (d) Reflective optical microscope pictures of the mixed white and black particles while the panel was moving. (e), (f) Migration and particle-clumping phenomenon pictures that were taken through a transmissive optical.

particle groups reduced the reflectivity, whereas the white particles mixed with black particle groups increased the reflectivity. The migration phenomenon of the particles explains the reduced reflectivity, as shown in Fig. 3(e).

As the times of movement increased, or the black or white particles moved to the barrier because of the migration phenomenon, the particles clumped. Fig. 4(f) shows a transmissive-optical-microscope picture of the particles after we removed the fluid after the movement. We can observe the clumping phenomenon, in which the particles are attached to each other in the form of a spot. Equation (3), which expresses the particles' movement distance (z) driven by the direction of the electric field, is related to the reflectivity. The mass of the particle, the electric charge, and the electric field is proportional to the movement distance (z). The decrease of electric charge results from an increase in mass, and a decrease in electric charge results from the particle-clumping phenomenon. As shown by equation (4), the decrease in electric charge is larger than the increase in mass, so the electric charge determines the decrease in movement distance (z).

Regarding the movement of the white particles, the electric field at a stabilizing point (0.06 V/μm) decreased by 20%, thus increasing the mass of the particles by 20%. Because the distance that particles can move between panels is fixed, the increased mass due to the particle-clumping phenomenon led to a decrease in z. After 2,000 instances of movement, the reflectivity ratio decreased, which caused a decrease in the breakdown electric field.

The rate of change in the electric field due to the movement of white particles was larger than that of the electric field due to the movement of black particles. From this fact, we can identify that the particle-clumping phenomenon usually occurs with white particles. As shown in Fig. 4(f), the reduced reflectivity and contrast ratio is caused by the particle-clumping phenomenon. The reflectivity of different levels of viscosity is represented in Fig. 4(b). By differentiating the level of viscosity in the panel, we measured the reflectivity. The reflectivity of white particles was high when the viscosity was low, whereas the reflectivity of black particles was high when the viscosity was low. We can identify that viscosity has a direct impact on the movement of particles. When the particles arrived in the upper ITO glass, they formed a chain by electric charges of particle. In other words, the relative electric charges of the particle caused them to have opposite polarities. Therefore, the repetitive pattern of particles with positive and negative polarities forms a chain. However, the particles in the chain were spread in the upper ITO glass during the applied electric field for a sufficient time period (a few hours). Because of the image force between the ITO glass and the particle is higher than the interacting force between the particles with opposite polarities. Here, the spread of the particle time is affected by the viscosity of the liquid. The reflectivity of widely spread particles was high compared with those particles that formed a chain. When the viscosity of fluid is doubled, the reflectivity decreases by 20%. However, for black particles, changes in reflectivity are less than 1%. In the same electric field, viscosity becomes a resistance. As a result, viscosity determines the movement distance (z). This means that the level of viscosity determines the reflectivity.

V. CONCLUSION

The movement mechanism of particles in fluid, with various factors such as fluid resistance, electric charge of particles, and electric field, is expressed in an equation that is based on Stokes' Law. We identified these equations through experiments. The electric capacity and current contribution particles are related to the stabilizing time of electric characteristic in the panel. Using equations (3) and (4), we can analyze the response time of particles and their reflectivity. The response time and reflectivity of a particle decreases according to the time of the movements.

A particle-clumping phenomenon is caused by the attraction between the same type of particles, and by the interaction between the fluid and the particles. The particle-clumping phenomenon led to an increase in particle mass and a decrease in charged particles. An increase in the viscosity of the fluid is caused by a decrease in response time. When we apply this to equations (3) and (4), we can identify that the decrease in response time is greater than a decrease in reflectivity.

The response time is proportional to the electric field and electric charge. Here, the mass of the particle has an impact on the gradient of falling time or rising time. The reflectivity is proportional to the electric charge, electric field, and mass of the particle. As such, after 2,000 instances of movement, the decrease in response time was six times larger than the decrease in reflectivity.

We can identify the change of viscosity in the fluid by the change in the q/m of the particles. When the viscosity of the fluid is doubled, the reflectivity decreases by 20%. The decrease in velocity caused by an increase in the particle mass is the reason for the reduced charge. This shows that we can analogize the reduced viscosity of a particle. Fluid convection and impact on the slipstream with particle to facilitate movement particle and partial particles unaffected by electric field, not mean the reduced fluid.

In this study, we analyzed particle movement by dielectrophoretic force. We can identify that the particle-clumping phenomenon has an impact on the characteristics of the movement of a particle. By differentiating the zeta potential, we can ease the attracting force between particles, thus improving the characteristics of panels. The results of these experiments provide basic data with which we can further analyze the mechanism of electric paper.

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