A 1-Dimensional Simulation Tool for Electrophoretic Displays

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Abstract

The microencapsulated electrophoretic display is a rapidly evolving technology suitable for application in paper-like reflective displays. This paper describes a one-dimensional simulation tool to investigate the internal behaviour of such displays.

1. Introduction

The working mechanism of electronic ink is very simple. The microcapsules contain positively charged white particles and negatively charged black particles suspended in a clear fluid. When a positive voltage is applied on the lower electrode, the white particles move to the top of the microcapsule and become visible to the user. This makes the surface appear white. At the same time the black particles will be pulled towards the bottom and will remain hidden. By reversing the pulse polarity, the black particles appear at the top surface, where they hide the white ones and make the surface appear dark at that spot.

It offers advantages such as ink-on-paper appearance, high reflectivity, good contrast ratio, wide viewing angle, image stability in the off state, and extremely low power consumption. [1]

2. Theoretical background

The simulation of electrophoretic ink displays consists of the motion of the particles under influence of an electrical field. The motion of charged particles is governed by drift (influence of an electrical field) and thermal diffusion, combined with the feedback of the particle charge on the electrical field. Equation (1) represents the change of ion concentration through time in one dimension [2]. \( n_i \) indicates the concentration of ion kind \( i \), \( D_i \) and \( \mu_i \) are the diffusion coefficient and the mobility, and \( E_z \) is the electrical field in the \( z \)-direction.

\[
\frac{\partial n_i}{\partial t} = \mu_i \frac{\partial}{\partial z} (n_i E_z) + D_i \frac{\partial^2 n_i}{\partial z^2} \quad (1)
\]

The calculation of the electrical field is given by the Poisson equation (2), where \( \rho(z) \) represents the charge distribution at position \( z \).

\[
\varepsilon \frac{\partial^2 E_z}{\partial z^2} = \rho(z) \quad (2)
\]

To solve these equations the method of finite differences is often used, which is appropriate if the characteristics of the different ions used are more or less the same. In electrophoretic displays this is not the case, because we also have to take into account the counter-charge particles [3] [4]. The charged colour-particles have a finite size and are usually treated as spheres (average radius 0.5 \( \mu \)m) with charge \( \pm Q = Z e \) (e: elementary charge), where \( Z \) can vary from 20 till 80 and it influences the mobility \( \mu_i \). To neutralize for example charge +\( Q \) the finite spheres have an ionic atmosphere of \( Z \) ions of charge \( -e \). Following the Einstein equation (3) the diffusion constant is inversely proportional with the charge number \( Z \).

\[
D_i = \mu_i \frac{kT}{Z e} \quad (3)
\]

The electrophoretic system consists of large particles which practically do not diffuse and smaller faster ions which diffuse strongly.

To overcome the difficulties of the electrophoretic system a Monte-Carlo algorithm has been used to calculate the transport of the charged particles [2]. The basic idea is not to solve differential equations (i.e. eq. (1)), but to track the motion of individual ions. An extra condition is added so that the concentration of the coloured spherical particles cannot exceed the closest sphere packing.

3. Simulation results

As a simulation example we used a cell thickness of 50 \( \mu \)m and calculated the transition from the black state towards the white state. The saturated black or white states are obtained by applying a +/-15V pulse for a long time to the ink. The particles are charged with \( Z = \pm 70 \), their concentration is \( 2 \times 10^{16} \) m\(^{-3} \), the radius 0.5 \( \mu \)m and the mobility is \( 1 \times 10^{10} \) m\(^2\)/Vs. Only the large coloured particles are calculated in this example.

In Figure 1 we can see the variation of concentration inside the cell with time for the white particles. The noise is due to the Monte-Carlo approach. Note that the black particles show a similar behaviour, but due to their opposite charge the concentration is mirrored in the cell. The maximum concentration is limited to the closest sphere packing (1.41*10\(^{19}\) m\(^{-3}\) for the present case).

In Figure 2 we can see the variation of concentration inside the cell with time for the white particles. The noise is due to the Monte-Carlo approach. Note that the black particles show a similar behaviour, but due to their opposite charge the concentration is mirrored in the cell. The maximum concentration is limited to the closest sphere packing (1.41*10\(^{19}\) m\(^{-3}\) for the present case).

The colour-particles stay near the boundary in a closest-packing-layer when the field is reversed. The thickness of this closest-packing-layer gradually decreases with time. The distribution inside the cell broadens, until all particles are moving towards the opposite side of the cell. We can see the closest-packing-layer decrease by comparing figures Figure 2 and Figure 3. This is an interesting result because for sufficiently low ion concentrations the layer would move as a broadening band towards the opposite side. How can we explain this?
The capsule is an insulator, of about 100 nm thick, between the electrode and the dielectric fluid. As positive particles are packed at one side of this capacitor structure, negative charges are accumulated on the electrode.

The total charge in this cell, of one kind of coloured particles, is 1% of the Space Charge Limit (Qscl) for passive matrix driving. Qscl is the charge over the capacitor of the two dielectric layers of the capsule when the voltage (V) of -1.5V is applied. This means that the charges inside the cell hardly influence the inner field distribution.

\[ \varepsilon_0 = \frac{\varepsilon_{\text{liquid}}}{\varepsilon_{\text{capsule}}} \]

\[ Q_{\text{SCL}} = C_{\text{Caps}} V = \frac{\varepsilon_{\text{liquid}} S}{2 d_{\text{Caps}}} V \]  

As the dielectric permittivity of the capsule and the liquid are approximately the same, the ratio of the capacitances of one capsule layer and the liquid is \( C_{\text{liquid}} / C_{\text{Caps}} \approx 500 \).

The important factor to determine if the charges inside the cell affect the distribution near the borders is the ratio of the absolute charge (Qe) brought on the electrodes when a voltage is applied, over the charge related to the motion of the ions Q0. The total cell capacitance can be approximated by the capacitance of the liquid and Q0 equals C_{\text{liquid}} V. The charge accumulated on the electrode due to the charge build-up by the closed-packing layer is the same as the charge in this packed layer Qe = \( \frac{1}{15} Q_{\text{SCL}} \).

The ratio Qe/Q0 is approximately 0.4 and indicates that Qe is larger than Q0. This means that we cannot neglect the capacitor effect of the plastic capsule near the electrodes.

Our initial situation at t = 0 s is that all coloured particles are in closest packing conditions near the boundaries. When the field is reversed, at t = 0 s, Q0 is positive at the positive electrode but Qe at that electrode is negative. This results in a local negative electric field even when a positive external field is applied. This local negative field will keep the positive white-particles near this boundary (Figure 2).

On Figure 3 we can see that this effect is still present after 250 ms. Although a positive external field is applied, we still have a local negative field. This causes the positive particles to stay near the boundary.

4. Conclusion

Charged particles can temporarily remain "stuck" on an electrode when the polarity of this electrode is reversed. This effect can be ascribed to the counter charge that is still present in an electrode after it has been in contact with a close packed layer of charged particle species. This "sticking" of charged particles near the boundary electrodes causes a gradual release of these particles into the fluid and should be visible in ion transport measurements.

This simulation tool can be used to evaluate the particle and field distributions in function of time, to optimise the electrophoretic devices.

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6. References


