 

# Electrophoretic Deposition of Liquid Toners in a Plate-Out Cell – An Numerical Analysis

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## Abstract

This numerical study was inspired by an intriguing experimental observation of some unexpected motion of “toner sheet” in a plate-out cell. In this report, numerical models for electrophoretic deposition of liquid toner are described. It takes into account the space-charge effect. The numerical results indicate that the toner deposition is strongly influenced by the space charge accumulation in a stationary plate-out cell. The motion of “toner sheet” gives a good indication of the charging characteristic of the liquid toner and other charged species, co-ion or counter ion, in the liquid inks. By comparison of numerical and experimental observation of the motion of toner in regular liquid inks, for example, it can be concluded that toner mobility is roughly an order of magnitude higher than the other charged species existed in the inks.

## Introduction

Liquid inks, suspensions of charged toner particles (pigmented resin) in non-conductive liquids, are used to tone latent images in liquid electrophotography. The charging of the liquid toner is established through acid-base chemistry.[1] Once chemical equilibrium is reached, there will exist multiple charged species of both polarities in the ink. The performance of liquid toning, given a toning process, is determined by the charge of the toner and the charge that is associated with other non-pigmented species. It is crucial to quantitatively measure the liquid ink charging properties in the process of ink design. A popular technique, *plate-out*,[2-4] is used to measure these charging characteristics. Liquid toner, placed between two parallel electrodes, is to be deposited on one electrode after application of electric fields. Other charged species, carrying either the same or opposite polarity of charge, the co-ions and counter-ions, will also move under field. Current measurement can be made as well as the visualization of the toner deposition process.

In this report, numerical models are described. Based on the first principal of charge transport, the electrostatic field is calculated, taking into account the space charge effect. The charge densities of all the charged species, including the toners, are calculated according to the conservation of the charge.

### Mathematical Modeling, Numerical Schemes, and Verification

Gauss’s Law:

$$\nabla^2 \phi = -\frac{1}{\varepsilon}\sum_i \rho_i \tag{1}$$

Conservation of charge:

$$\frac{\partial}{\partial t}\rho_i + \nabla \bullet \left(\rho_i \mu_i \mathbf{E}\right) = 0 \tag{2}$$

$\rho_i$ is the charge density of species ***i.***, $\mu E$ is the electrophoretic velocity, which is the product of mobility and local electrostatic field. $\phi$ and $\varepsilon$ are the electrostatic potential and permittivity of the carrier liquid. An upwind finite difference scheme and a rectangular mesh are used to solve equation (1-2).[5]

The numerical models have been verified by an unsteady (time-transient) problem, defined in table 1, which has an exact solution, as shown in equation (3). The current density, *J*, is the summation of the free current due to the motion of all the charged species, $\rho\mu E$, and the displacement current, $\varepsilon(dE/dt)$. The problem is defined in a typical plat-out cell setup where the two electrodes are placed 200 μm apart with 100V potential difference. The exact solution uniquely exists due to the assumption that there is a pair of charged species but only one is mobile under field. The numerical solution is matched favorably with the exact solution,[6] as shown in figure 1.

$$\begin{aligned} J(t) &= \rho\mu E + \varepsilon \frac{dE}{dt} \\ &= -\frac{\rho\mu}{L}\left(1 - \frac{D}{L}\right)\left(\phi - \frac{\rho D^2}{2\varepsilon}\right) \\ D(t) &= \sqrt{\frac{2\varepsilon\phi}{\rho}} \tanh\left(\frac{\mu}{L}\sqrt{\frac{\rho\phi}{2\varepsilon}}t\right) \end{aligned} \tag{3}$$

**Table 1.**

| Gap (L) | Initial charge density (ρ) | Mobility (μ) | Ink permittivity (ε) | Potential difference ($\phi$) |
|---|---|---|---|---|
| 200 μm | +3.85 / -3.85 Coul/$m^3$ | 0 / 0.54 $mm^2$/KV-s | 1.77E-11 Farad/m | 100V |

 

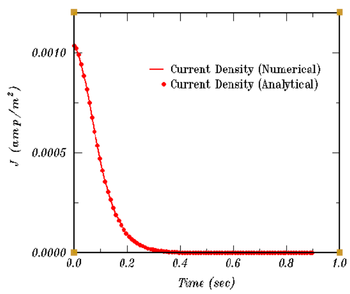


*Figure 1. Model verification: numerical vs. exact solution*

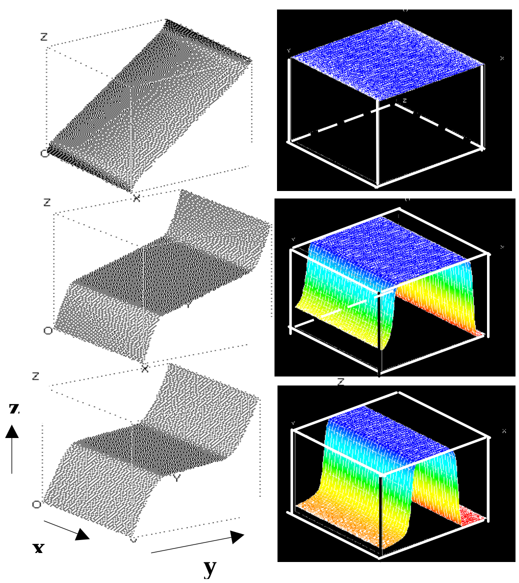


***Figure 2.*** *Distribution of potential (left) and toner charge density (positive species) concentration (right) in time (from top down)*

## Plate-out Fundamentals – A Numerical Perspective

A typical numerical result of the plate-out can be represented by the plots of potential and charge density (only positive species shown) in time, as shown in figure 2. In both plots, the z-axes (height) represent the magnitudes. The gap is in the y direction. If the gap is relatively smaller than the size of the plate (in x), it becomes a one-dimensional problem, as shown in figure 2. Two charged species, with same mobility but opposite in charge, are calculated. For the positive charge distribution, two "clear zones" can be identified immediately adjacent to both electrodes. One clear zone shows a sharper transition in the charge density. It can be seen also that while the toner is being deposited to one electrode (deposited toner not shown) the toner density remains mostly unchanged in the middle section of the gap. In this area, the electrostatic field, which can be recognized by the slope of the potential, is quickly reduced. The current density in time is plotted in figure 3. It decays monotonically in time due to the field diminishing, which is caused by the accumulation in space charge, as shown in figure 4.

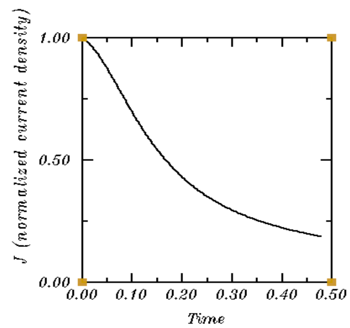


*Figure 3. Current density in time*

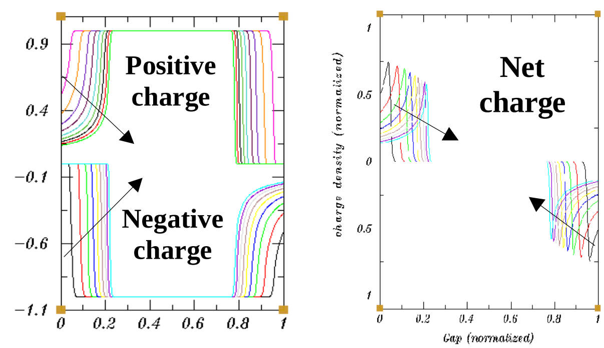


*Figure 4. Charge densities (left), for both positive (toner) and negative charged species, in time, and, the net charge (right) distribution in time (The arrows indicate the sequence in time).* ***The mobility of the positive and negative charged species are the same.***

## Experimental Observation

The previously calculated charge distribution (in figure2-4) has never been observed in the laboratory when "regular" liquid toners were tested. The charge distribution can be obtained by the visualization of the toner concentration, the motion of the "toner sheet", which can be captured by a video camera. A typical observation can be represented by figure 5. The salient features are: (1) the apparent toner sheet is progressing, as a whole, toward the electrode that the toner particles are being deposited to; (2) a "clear zone" appears increasingly at the opposite electrode. Contrary to the two clear zones appeared in the case of figure 2, there is only one in the present case. A rather abrupt and sharp interface of the clear zone and toner sheet can be seen.

 

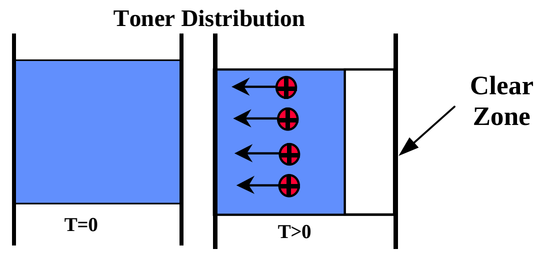


*Figure 5. A "progressing" toner sheet is moving toward the electrode, to which toner particles are being deposited.*

To obtain such distinct features, a numerical solution, in figure 6, is obtained where the mobility of the positively charged toner is one order of magnitude larger than the one of the counter charged species. It is interesting to note that although there is an order of magnitude difference in mobility, the difference in the charge depletion in the gap between the two polarities is rather small. Space charge changes the field in such a fashion that the lower mobile particles tend to be accelerated by the higher field. It is also interesting to note that the negatively charged species, while being deposited to the right electrode (at gap=1.0), its distribution in space is shrinking toward the left electrode. It is opposite to the "***progressing*** sheet" of the positive charge and is therefore referred to as a "***receding*** sheet"

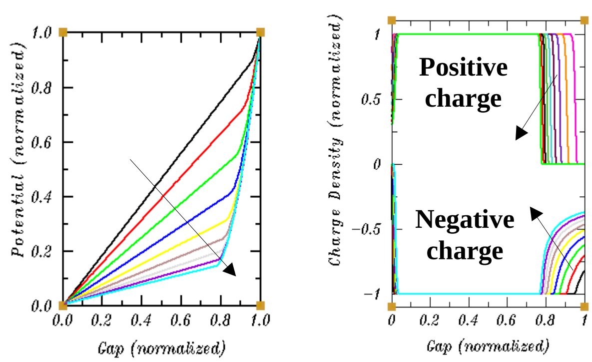


*Figure 6. Charge densities (right), for both positive (toner) and negative charged species, in time, and, the potential (left) distribution in time (The arrows indicate the sequence in time). The mobility of the positive charged species is 10 time faster than the negative one.*

A rather intriguing plate-out has been observed[7] with the use of certain liquid inks. It can be described by the drawing in figure 7. While the toner being deposited, there is a visible increase in toner concentration at the interface with the clear zone. The region of the increased toner concentration grows in size as the deposition process proceeds.

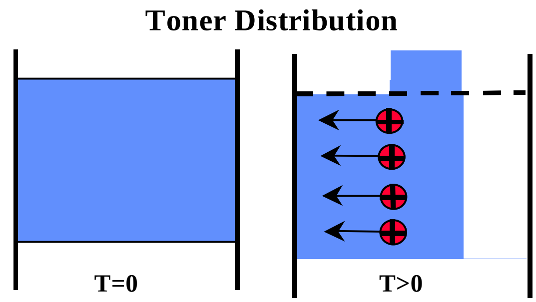


*Figure 7. A progressing toner sheet plus an intriguing surge in toner concentration at the interface with the clear zone.*

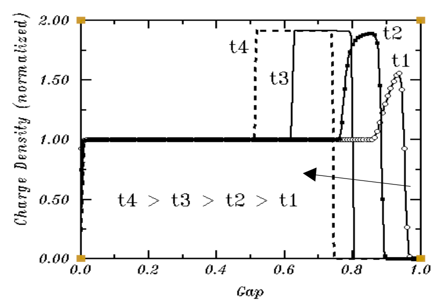


*Figure 8. Charge density of the toner in time (The arrows indicate the sequence in time, $t_4>t_3>t_2>t_1$). The toner mobility is 10 time faster than the counter-ions but ten times slower than the co-ions.*

This observation can be conceived by the following numerical results. Three charged species are assumed in the calculation. While it is similar to the previous case (figure 7), where the positively charged toner has mobility ten times faster then the counter charged species, there is yet another fast moving co-ion (same charge polarity of the toner) whose mobility is another ten times higher than the toner. The toner and the co-ion are assumed to have the same initial charge density and, hence, the counter-ion has twice as much of the initial charge density. It can be seen in figure 8 that while the toner sheet is progressing toward the left electrode, the toner concentration increases indeed at the interface adjacent to the clear zone. The corresponding charge distributions in time for co-ion and counter-ion are shown in figure 9-10 respectively. It can be better understood by examining the distribution of potential and the net charge, as shown in figure 11-12. As the plate-out starts, the fastest moving co-ions quickly bring on space charge in the zone where neither the toner nor the counter-ion has moved very much. In this zone, which close to the right electrode, the space charge changes the local field enough that the toner is accelerated by the higher field. It is the regional acceleration that results into the increase of local toner concentration. There are two visible peaks in the net charge distribution (figure 12), which indicates the locations of the two fronts of toner and counter-ion sheets.

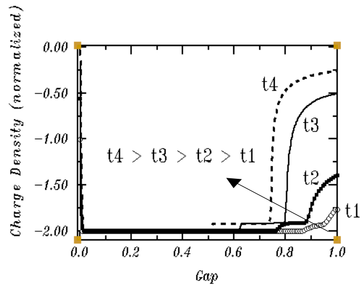


*Figure 9 Charge densities of the counter-ions.*

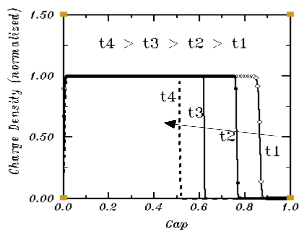


*Figure 10 Charge densities of the co-ions.*

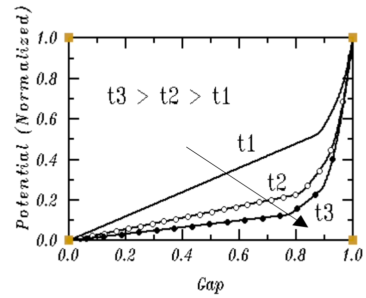


*Figure 11 Potential distribution in time.*

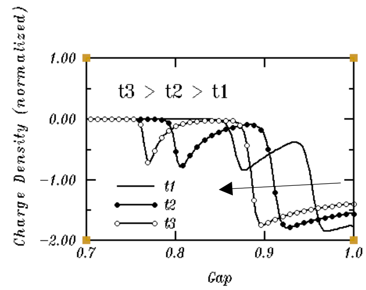


*Figure 12 Distribution of the net charge in time. (only part of the gap, gap = 0.7 to 1.0, is shown)*

## Summary

In a stationary plate-out cell, the space charge effect strongly influences the motion of charge species. The space charge effect is further enhanced if large differences in mobility among the various charged species exist. Some peculiar features of the toner sheet motion, like the increase in toner concentration, give good indication of the charging characteristics of the liquid toners. In cases where less space charge effect occurs, like in a development nip of a two-roller developer where space charge accumulation is reduced by the replenishing fluid flows, the toner movement ought to behave differently.

## References

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