

Electrical Simulation of Liquid Development for Electrophoresis

I. Chen, J. Mort and M. A. Machonkin
Wilson Center for Research and Technology, Xerox Corporation,
Webster, NY

Abstract

Liquid immersion development of latent electrostatic images has been described by the transport equations for charged toners and counter-ions. Since the charge density in the development gap is, in general, comparable to or greater than the latent image charge density (e.g. on the photo-receptor), the charge transport is expected to be space-charge perturbed or limited. This paper reports an electrical experiment which provides not only a direct observation and confirmation of the space-charge effects in liquid development, but also serves as a novel characterization technique for the electrical properties of liquid developers in an environment closely simulating the actual development zone.

Introduction

The electrophoresis of toner particles in liquid immersion development (LID) of latent electrostatic images has been described by charge transport theory with various degrees of sophistication. In the work before 1975, it was generally assumed that the toners moved independently in the uniform field generated by the imagewise charge, neglecting the interaction with the space charge due to other toner particles and counter-ions.^{1,2} Following the failure of this simple model to account for the experimental observations, treatments taking into account of the space-charge effects have been published by many authors.³⁻⁷

In this paper, we report a joint theoretical and experimental investigation which provides a direct evidence that electrophoresis in liquid development is indeed space-charge-perturbed (SCP) as described by the charge transport theory. Since the "series-capacitor" discharge technique used in this investigation is a purely electrical measurement, and does not involve optical detection, the technique is equally applicable to inks and samples containing only the molecules and aggregates of charge director (CD) surfactants. This provides a novel means for a comparative study of the electrical properties of dispersions with and without the presence of toner particles. The theoretical background and the experimental technique are briefly described below. More details can be found in a separate publication.⁸

Theoretical Background

To simulate the electrophoresis occurring in LID, consider an experimental setup consisting of two capacitors connected in series as shown schematically in Figure 1. One capacitor is a perfect dielectric, which simulates the imaging member bearing the latent electrostatic images, Q_s . The other comprises a film of ink sample, or more generally, a colloidal dispersion. While in the actual LID, the driving force for the electrophoresis is the charge Q_s at the interface, in the present experiment it is replaced by an equivalent bias voltage, V_b , applied at the top electrode. Although the bias voltage applied is constant in time, the sample layer voltage decays as charge species move within the liquid. Thus, the voltage decay in the sample layer can be observed by the measurements of external currents J_T . It is also noted that the phenomenon is essentially equivalent to what is commonly known as "dielectric relaxation", except that the non-Ohmic supply and transport of charge species introduces new features as described below.

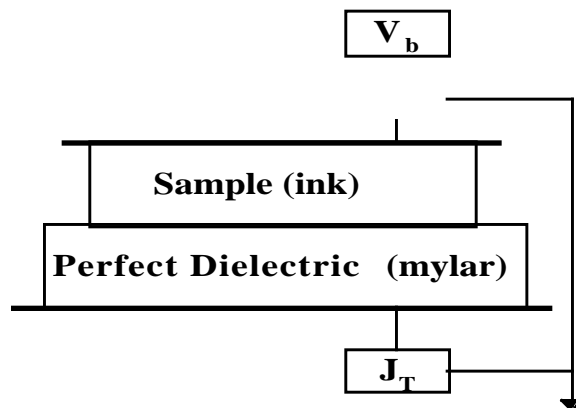


Figure 1: Schematic diagram for the series-capacitor experiment.

Applying the same charge transport theory which has been used to describe LID process,³⁻⁷ the total current J_T can be calculated from numerical solutions of the coupled continuity and Poisson's equations, together with appropriate boundary conditions, using the expression,⁸

$$J_T(t) = -[1/L_s(1+C_s/C_d)] \int_0^L S_k(\mu_k \rho_k) E dx$$

where L_s is the sample thickness, C_s and C_d are the capacitance of the sample and the perfect dielectric, respectively, μ_k and ρ_k denote the mobility and density, respectively, of the k -th charge species, and $E(x)$ is the local electric field.

Figure 2 shows examples, in which the bias voltage is assumed to have a value $V_b = \rho_0 L_s^2 / \epsilon_s$, where ρ_0 , L_s and ϵ_s are the charge density, thickness and permittivity, respectively, of the sample. Thus, the total charge per unit area of sample, $\rho_0 L_s = (\epsilon_s / L_s) V_b$, is equal to one-CV's worth. The three curves differ in the counter-ion mobility, $\mu_{ci} = 1, 0.1,$ and 0.01 , in units of the toner mobility μ_t .

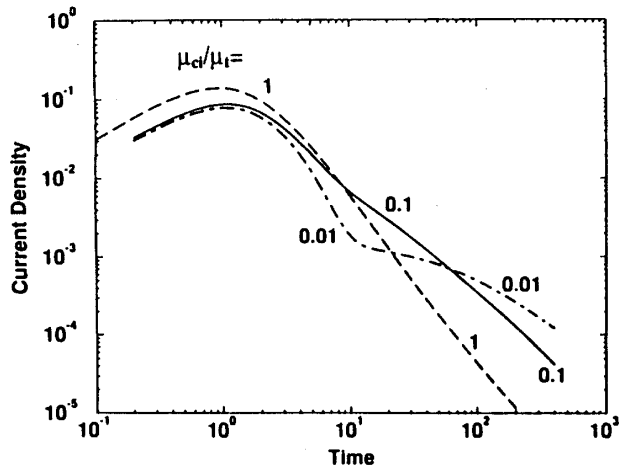


Figure 2. Current density vs time calculated for three values of counter-ion mobility to toner mobility ratios, μ_{ci}/μ_t .

The decay of J_T with time is slower than exponential (expected from the equivalent-circuit approximation of dielectric relaxation), and approximately follows a power law, t^{-n} , with $n \approx 2$ for $\mu_{ci}/\mu_t = 1$ and smaller for others. This behavior is similar to that of well-known space-charge-perturbed transport of charge injected from one electrode.⁹⁻¹¹ The observation of this feature at a given bias voltage V_b indicates the charge density to be of the order of $\rho_0 \approx C_s V_b / L_s$.

The charge species in the above examples are assumed to be generated after the bias voltage is applied. Only with these conditions can the current increase at short times be accounted for. The observed maximum arises because of the competition between the generation of charge species and their arrival at the boundaries. It has been shown that the time of current peaks coincides well with the nominal transit time. Thus, knowing the thicknesses, capacitances and the bias voltage, effective mobilities can be determined.

Experimental Studies

The ink samples used in the studies described here consisted of particles 1–2 μm in diameter of a copolymer of ethylene and methacrylic acid, available from DuPont as Nucrel resin, which also contained a cyan pigment as a colorant.¹² The

charge director (surfactant) was an AB diblock quaternary ammonium polymer (hereafter referred to as Quat) of two molecular weights, 4,000 and 93,000 (4K and 93K).¹³ The carrier fluid was an aliphatic hydrocarbon with a viscosity at 25C of ~ 6 cps. The formulations of the samples were comprised of 2 wt% resin with either 30 mg of 4K or 100 mg of 93K Quat per gram of toners (referred to as 30:1 and 100:1 respectively). Charge director solutions containing the same weights of the charge director, but without toners, were also examined.

Sheets of 25 μm mylar placed on a polished aluminum block electrode serve as the "perfect" capacitor. A known amount of the sample solution (~ 0.13 cc) is placed on the mylar such that on covering it with another aluminum plate (5×5 cm), the solution flows to fill the entire area of 25 cm^2 . Knowing the carrier fluid density and weight of the sample, the thickness of the liquid layers so formed was calculated to be ~ 60 μm . Some measurements were made using a cell giving liquid thickness of ~ 125 μm .

Figure 3 provides a panoramic perspective of a typical experimental current vs. time curve obtained for a fixed bias voltage of 400V. The plot in logarithmic scales covers 5 orders of magnitude in current and time, for a sample containing 2 wt% toners and 30:1 4K Quat in hydrocarbon and the corresponding CD solution containing no toner particles.

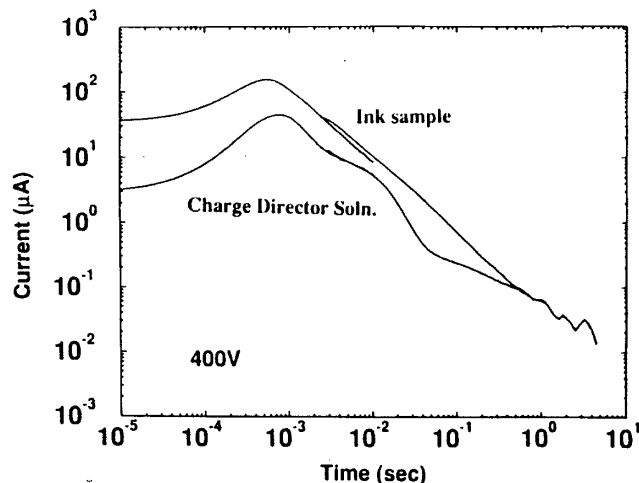


Figure 3. Current vs time for an ink sample and a charge director solution, measured at a bias voltage, $V_b = 400\text{V}$.

The observed current characteristics have no resemblance to the exponential form expected from the equivalent-circuit approximation, namely, where an Ohmic supply and transport of charge species occurs. On the other hand, the general feature of space-charge-perturbed transport, predicted by the charge transport theory, i.e. the decay of current density according to the power law (t^{-n}), is clearly seen (cf. Figure 2). This confirms the applicability of the charge transport theory to space-charge-perturbed electrophoresis in LID.

Significant difference in the results for the CD solution without toner and the ink sample can be noted. In the former

case, there is clearly structure which is absent in the latter. In addition, in both cases, there is a rise in the current at the earliest times which means that the charge density in the sample is increasing by some time-dependent, and field-induced, generation mechanism. The complex structure found for the charge director solution indicates that a number of charge species, with significantly different average mobilities are involved. Indeed, according to the data shown in Figure 2, a mobility differential between the fast and slow charge species of from one to two orders of magnitude, which also reduces the logarithmic slope (i.e. the power n) of decreasing current, is needed to yield the structure seen in the experimental data. Finally, a combined lack of the slower charge species in the ink sample with an overall enhanced current level compared with the CD solution is noted and will be discussed later.

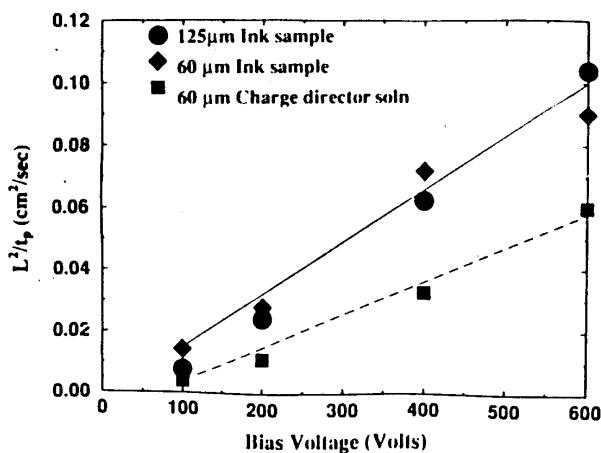


Figure 4. L^2/t_p vs bias voltage plots for inks of two sample thicknesses, and for 4K Quat charge director solution. The slopes of the connecting lines are used to determine the mobilities.

Figure 4 shows a plot of L_s^2/t_p , (where t_p is the time at the peak current) versus the bias voltage for the two sample thicknesses. Identifying t_p as the transit time, i.e., $t_p \approx L_s^2/\mu V_b$, where μ is an effective mobility, the linearity of these plots and their extrapolation to the origin is another important confirmation of the identification of this as being a transport phenomenon, but additionally indicates that for fields greater than 10^4 V/cm it involves a field-independent mobility. The slope of this plot yields an effective mobility of $\mu \approx 10^{-4}$ cm²/Vs.

From the enhanced peak current of the ink versus CD solution, the dominant charge species are identified as the toner particles. By comparison with the theoretical

prediction (Figure 2) the long-time features of the experimental curves in Figure 3, particularly those for the ink, suggest that for the conditions operative in the experiment, the voltage decay is in the space-charge-perturbed regime. Therefore, the total charge per unit area of sample is of the order of one CV's worth at the applied bias voltages of 400 volts. Thus, using the values of the capacitance $C \approx 10^{-10}$ F/cm², and the sample thickness $L_s \approx 60 \mu\text{m}$, the sample charge density is estimated to be of the order of $\rho \approx 10 \mu\text{C/cm}^3$. Using these values of ρ and μ , and the initial applied field ($\approx 10^4$ V/cm), the peak current density can be expected to have a value of the order of 10^{-5} A/cm², which is in good agreement with the experimental values (for 25cm²), indicating the consistency of the deduced values. It is worth noting that with these values of μ and ρ , the product, or the conductivity of the ink sample, has a value of the order of 10^{-9} S/cm. This value is about two orders of magnitude larger than values obtained with the conventional low field ac measurements,¹² and reflects the consequence of a continuous charge generation during the application of dc bias corresponding to a high field of $\geq 10^4$ V/cm.

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