The Role of Dielectric Relaxation in Media for Electrophotography (I) Modeling of Electrostatic Transfer

Inan Chen and Ming-Kai Tse
QEA, Inc.
Burlington, Massachusetts, USA

Abstract

A mathematical model of electrostatic transfer is developed in which dielectric relaxation in the receiving media is analyzed with a first principle treatment of charge transport. The charge density and mobility requirements for achieving full transfer in a given process time are shown to be sensitive to transport conditions such as the charge injection at the contacts and the field dependence of mobility.

Introduction

In electrostatic (ES) transfer of developed toners to paper or intermediate belts (i.e. receiving media – hereafter “receiver”), a bias voltage is applied across a multi-layer consisting of the receiver, the toner layer, the photoreceptor, and a small air gap. It is commonly understood that successful toner transfer requires a reversal of the field direction in the toner layer in order to drive the toner away from the photoreceptor and towards the receiver. Because of the large thickness of receiver compared to that of other layers, successful transfer is made possible by dielectric relaxation in the receiver, causing the shift of a large fraction of the applied voltage to the toner layer. Traditionally, dielectric relaxation is analyzed by an equivalent circuit, representing the layers by their resistances and capacitances.[1] However, experimental data on semi-insulating materials, such as those used for transfer media, have shown that relaxation does not always follow the exponential time dependence predicted by the equivalent circuit model.[2,3]

A mathematical model of charge transport, taking into consideration space charge effects and features such as non-Ohmic charge injection, charge trapping, and field dependent mobility, has been developed for analyses of open-circuit and closed-circuit measurements on semi-insulators.[3,4] In this paper, we report the application of the model to dielectric relaxation in ES transfer. The independent roles played by the two components of conductivity (or resistivity) – namely, charge density and mobility – in transfer efficiency are analyzed. It is shown that, the charge density determines the extent of transfer, while the charge mobility determines the time required for achieving the transfer. Thus, in high-speed printers with a limited process time, it becomes important to specify the minimum requirements for both charge density and mobility, and not just their product – conductivity. The general rules for these requirements with respect to process speeds are discussed in the following.

Space-Charge Model of Electrostatic Transfer

A one-dimensional schematic of the multi-layer configuration at the transfer nip is shown in Fig. 1. The photoreceptor (PR) and the air-gap are assumed to be space charge free, and hence, the fields E_p and E_a are spatially uniform. The toner layer is assumed to have a constant volume charge density q_t, and thus the field $E_t(x)$ is a linear function of q_t and x. The receiver has an intrinsic conductivity $\sigma = (\mu_p + \mu_n)q_i$, where the μ’s are the drift mobilities of positive and negative charge, and q_i is the intrinsic charge density.

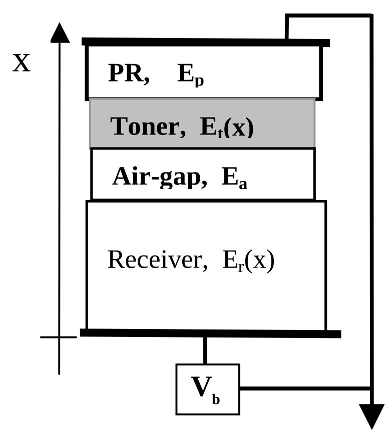

Figure 1. One-dimensional schematic of transfer nip

When a bias voltage V_b is applied across the multi-layer, the conduction current due to the intrinsic charge and the injected charge from the bias electrode flows in the receiver. This causes the voltage across the receiver to decay with time, and the voltages across other layers to increase with time, such that a constant voltage V_b is maintained across the multi-layer. The field in the receiver $E_r(x)$ can be calculated from the space charge densities according to the Poisson equation,

$$\partial Er(x,t)/\partial x = [qp(x,t) + qn(x,t) + qd(x,t)]/\varepsilon r \qquad (1)$$

where ε_r is the permittivity of the receiver, and q_p, q_n and q_d are the densities of holes, electrons, and deep trapped charges, respectively, in the receiver. The time evolutions of charge densities are given by the continuity equations,

$$\partial q_p/\partial t = -\partial(\mu_p q_p E_r)/\partial x - q_p/\tau_p \qquad (2a)$$

$$\partial q_n/\partial t = -\partial(\mu_n q_n E_r)/\partial x - q_n/\tau_n \qquad (2b)$$

$$\partial q_d/\partial t = q_p/\tau_p + q_n/\tau_n \qquad (2c)$$

where τ_p and τ_n are the lifetime to deep trapping for holes and electrons, respectively.

The drift mobility can be field dependent. For lack of better knowledge, it is assumed to have the following power-law dependence, with μ_o denoting the mobility at a nominal field E_o:

$$\mu_p(E) = \mu_{po}(E/E_o)^k; \quad \mu_n(E) = \mu_{no}(E/E_o)^k \qquad (3)$$

where the power k may not be the same for holes and electrons.

The field in layer 1, E_1, at the interface and that in layer 2, E_2, are related to the interface charge density Q_{12} by the Gauss theorem,

$$\varepsilon_2 E_2 - \varepsilon_1 E_1 = Q_{12} \qquad (4)$$

where ε_1 and ε_2 are the permittivities of layer 1 and 2, respectively.

The charge injection into the receiver from the bias electrode is specified by assuming the injection current $J_p(0,t)$ to be proportional to the field at the boundary,

$$J_p(0, t) = s_p E(0, t) \qquad (5)$$

Note that the proportionality constant s_p has the dimension of conductivity.

Starting with the initial conditions that the receiver is charge neutral, that there is no charge accumulation at the receiver/air-gap interface, and that the layer voltages are divided capacitively at t = 0, the fields and voltages in each layer can be calculated as functions of time from the above equations by numerical iteration.

Before presenting the numerical results, let us examine typical numbers for the electrical parameters in common transfer media, e.g. paper.

The conductivity is of the order of $\sigma \approx 10^{-10}$ S/cm, and the permittivity is about $\varepsilon_r \approx 5x10^{-13}$ F/cm. This gives the dielectric relaxation time of $\tau_{dr} = \varepsilon/\sigma \approx 5$ msec.

The typical thickness is $L_r \approx 10^{-2}$ cm. For a bias voltage of $V_b \approx 10^3$V, the surface charge density, i.e. "one CV's worth," of charge is $\approx 5x10^{-8}$ C/cm^2.

The charge mobility in these media is not well known, but is expected to be of the order of $\mu \approx 10^{-6}$ cm^2/Vsec (or less). Then, the nominal transit time defined by,

$$t_T \equiv L^2/\mu V_b \qquad (6)$$

has a value $t_T \approx 0.1$ sec, which is longer than the relaxation time τ_{dr}. With the same mobility, the total intrinsic charge in the layer is $q_i L_r = (\sigma/\mu)L_r \approx 10^{-6}$ C/cm^2, which is larger than one CV's worth of charge.

The charge transport under these conditions, $t_T \geq \tau_{dr}$ and $q_i L_r \geq CV$, is known to be in the regime where space charge effects become significant. In ES transfer, the voltage across the receiver decreases with time, making the actual transit time longer, resulting in more pronounced space-charge effects as the dielectric relaxation proceeds.

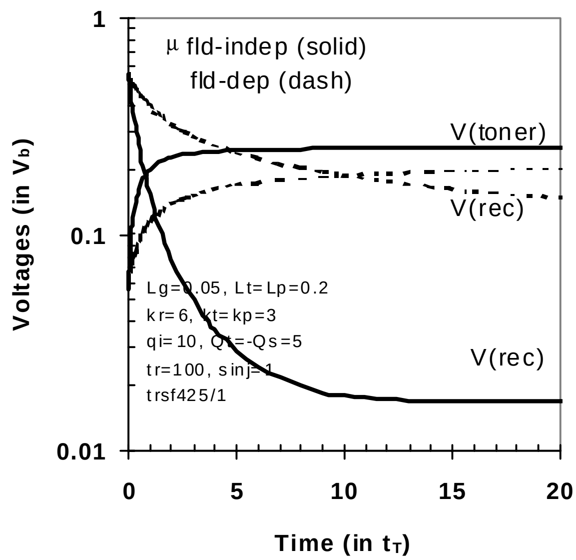

Figure 2. Examples of receiver and toner layer voltages from the space-charge model for field independent mobility (solid curves), and for field dependent mobility with k=2 (dashed curves)

Layer Voltages

Figure 2 shows the time evolution of receiver and toner layer voltages calculated with the space-charge model using a set of typical values for the parameters (given on the figure). The voltage is in units of V_b. The time is in units of t_T. In the case of field dependent mobility, t_T is defined with the mobility μ_o at the nominal field $E_o = V_b/L_r$, using Eq.(6). In both cases, the decay of the receiver voltage can be seen to deviate from the simple exponential at large times. A comparison of the two cases indicates that the space-charge effect is enhanced by field dependent mobility. Here, the lifetime to deep trapping is assumed to be very long ($\approx 100t_T$). Therefore, this deviation from the exponential decay is a consequence of the mobile space-charge effect. Calculations are repeated to confirm that these features are qualitatively independent of the choice of parameter values within the range of practical interest.

Transfer Efficiency

The field in the toner layer is given by,

$$E_t(x) = E_{ta} + q_t(x - x_{ta})/\varepsilon_t \quad (7)$$

where E_{ta} is the field at the toner-air interface x_{ta} and ε_t is the permittivity of the toner layer. For positive toners to be transferred, this field must be negative. Thus, the amount of toner transferred can be determined (neglecting the adhesive forces) by the position x where the field $E_t(x)$ changes sign. The transfer efficiency is then given by the ratio of such $(x - x_{ta})$ to the toner layer thickness L_t.

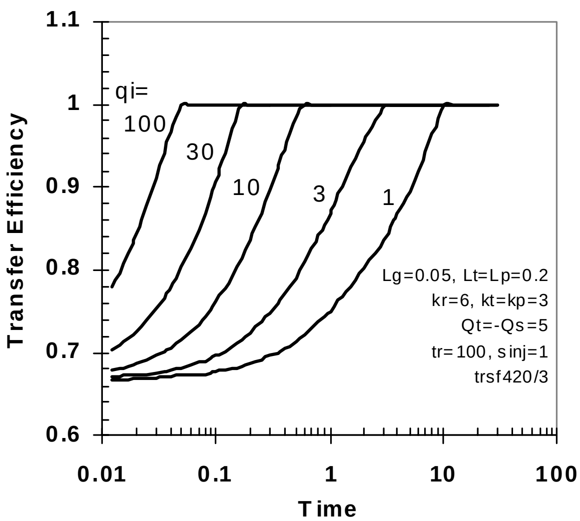

Figure 3. Transfer efficiency vs. time for various intrinsic charge densities qi, calculated for filed-independent mobility.

Calculated examples of transfer efficiency as the time evolves are shown in Fig.3 for samples with various intrinsic charge densities q_i, assuming a good injection from the electrode and long lifetime. q_i is given in units of q_o defined by,

$$q_o \equiv \varepsilon_o V_b / L_r^2 \quad (8)$$

with ε_o = permittivity of vacuum.

A full transfer, i.e. transfer efficiency reaching unity, is important in preventing color shifts. It can be seen that the time to reach full transfer increases as q_i decreases. For a small $q_i \le q_o$, it has been found that a full transfer may never be achieved, especially in the case of field-dependent mobility.

Using the data in Fig. 3, the time to reach full transfer as a multiple *m* of the time unit ($t_F = m t_T$) is plotted versus the intrinsic charge density as a multiple *n* of q_o ($q_i = n q_o$) in Fig. 4. The solid curves are for the case of field independent mobility (from Fig.3) and the dashed curves are for the case of mobility that is quadratically dependent on the field. The curves for the product *mn* vs. *n*, to be discussed later, are also shown.

Discussion

In principle, the process time t_{proc} must be long enough for full transfer,

$$t_{proc} \ge t_F = m t_T = m(L_r^2/\mu_o V_b) \quad (9)$$

Thus, using Eq.(6) for t_T, the mobility must have a minimum value related to the layer thickness L_r, the bias V_b, and the process time as,

$$\mu_o \ge m(L_r^2/t_{proc} V_b) \approx m(10^{-6}\ cm^2/Vsec) \quad (10)$$

For a process time of 0.1 sec, and the typical thickness $L_r \approx 10^{-2}$ cm and bias $V_b \approx 10^3$V, the quantity in parentheses has a value of 10^{-6} cm^2/Vsec.

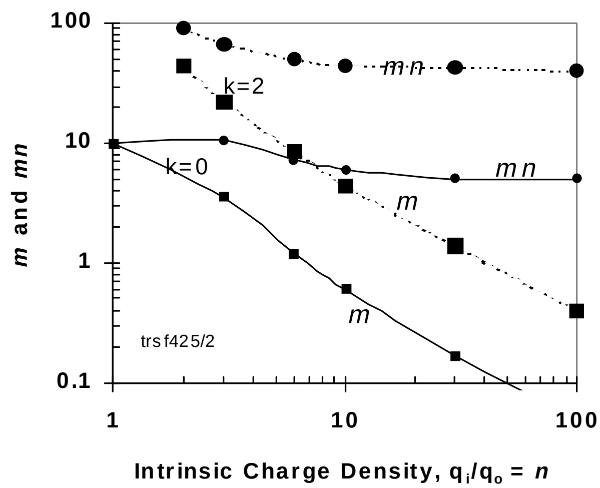

Figure 4. Time to full transfer m (in t_T), vs. intrinsic charge density n (in q_o), and the product mn vs. n, for field independent (k=0) and dependent (k=2) cases (with strong injection).

More plots of *m* vs. *n* are shown in Fig. 5. In the three solid curves, the injection from the bias electrode is varied, with the injection level s given in units of ($\varepsilon_o \mu_o V_b / L_r^2$). The dashed curves show the corresponding data for the case of mobility asymmetry, with the hole mobility μ_p=0. The increase in *m*, and hence the required mobility, at low q_i (or *n*) is enhanced by weak injection.

In terms of *m* and *n*, the required conductivity can be expressed using Eqs. (8) and (10) as,

$$\sigma \approx \mu_o q_i \ge mn(\varepsilon_o/t_{proc}) \quad \approx mn(10^{-12}\ S/cm) \quad (11)$$

With t_{proc} = 0.1 sec, the quantity in the bracket in Eq.(11) is about 10^{-12} S/cm. It can be seen from Figs. 4 and 5 that *m* varies approximately as 1/*n* for larger values of q_i ($\ge 6q_o$). Thus in this range, the product *mn* is constant (as shown in Fig. 4), having a value of about 5 for the case of field independent mobility (k = 0) and about 50 for the case of field dependent mobility with k = 2.

The large difference (by one order of magnitude) in the conductivity requirements between the cases of field independent and dependent mobility shown in Fig. 4 means that it is important to be able to detect the field dependence of mobility in media characterization. In a separate publication,3 we have demonstrated that the detection of field dependent mobility is more convenient in open circuit measurements than in closed circuit ones. Therefore, open circuit techniques, such as the ECD technique,5 can provide more relevant information on the electrical properties of receivers than can closed circuit techniques.

In the low q_i ($\leq 6q_o$) regime, the product *mn* deviates from and is larger than the constant value at large q_i. Furthermore, the required *m* value (i.e. the mobility) for a given q_i depends on the rate of charge injection from the bias electrode, and on whether both holes and electrons are equally mobile (as shown in Fig. 5). In other words, in this regime the specification of conductivity alone is not sufficient for the prediction of transfer efficiency. Other transport parameters, such as the nature of charge injection and charge mobility, do influence the transfer efficiency.

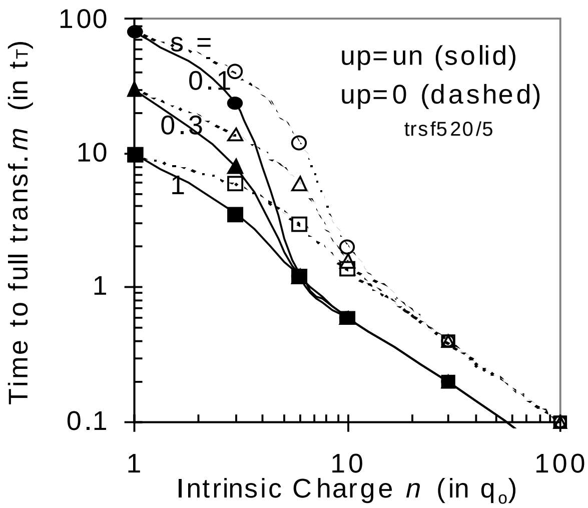

Figure 5. Plots of m vs. n (as in Fig. 4), but with 3 different injection levels s. Dashed curves show the case where the hole mobility is zero.

Summary and Conclusion

In summary, we have applied the first principle treatment of charge transport to dielectric relaxation in receiving media during ES transfer. The transfer efficiency is calculated as a function of time and intrinsic charge density q_i. This provides a way to determine the minimum charge mobility required for achieving full transfer within a given process time.

The traditional way of predicting the performance of a receiver by its conductivity is shown to be insufficient. An increase in the process speed increases the required charge mobility. The increased charge mobility requirement may not be satisfied by increased conductivity if the latter increase is in the other component – charge density. If the mobility is field dependent, and decreases with the relaxing field, the required initial mobility must be larger (by as much as an order of magnitude). In addition, the mobility requirement is also dependent on the rate of charge injection from the bias, and on whether both positive and negative charges are equally mobile.

Thus, a complete characterization of a receiver for its performance in ES transfer must be carried out under conditions closely simulating charge supply and transport in the actual printing application. The open circuit measurements of the electrostatic charge decay (ECD) technique, with the sample wrapped around a typical roller shaft, provides the necessary conditions.[5, 6]

References

1. M. C. Zaretsky, *J. Imag. Sci. & Tech.* **37**, 187 (1993); J. W. May and T. N. Tomb, Electrostatic toner transfer model, *Proc. NIP13*, pg.71 (1997); T. N. Tomb, Electrostatic toner transfer to an intermediate: Results from a continuum model, Proc. *NIP14*, pg.440 (1998)
2. M. K. Tse and I. Chen, The role of dielectric relaxation in charge roller performance, *Proc. NIP14*, pg. 481 (1998)
3. I. Chen and M. K. Tse, Electrical characterization of semi-insulating devices for electrophotography, ***Proc. NIP15, pp. 486-489***, (1999)
4. I. Chen, J. Mort, M. A. Machonkin, J. R. Larson, and F. Bonsignore, *J. Appl. Phys*. **80**, 6796 (1996)
5. M. K. Tse, D. J. Forest, and F. Y. Wong, Predicting charge roller performance in electrophotography using electrostatic charge decay measurements, *Proc. NIP11*, pg.383 (1995)
6. M. K. Tse, D. J. Forrest and F. Y. Wong, The role of dielectric relaxation in media for electro-photography (II) – Imaging electrostatic non-uniformity in paper, ***Proc. NIP15, pp. 159-163,*** (1999)

Biography

Inan Chen received his Ph.D. from the University of Michigan in 1964. After a year of post-doctoral research there, he joined Xerox Research Laboratories in 1965 and retired in 1998. Currently he is associated with QEA, Inc. as a consulting research scientist. He has (co)authored over 100 publications, including eight US patents, in the fields of materials, devices and processes related to electrophotography. E-mail: inanchen@aol.com or mkt@qea.com