Electrostatic Transfer of Color Images in Electrophotography

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Abstract
A popular technique in color electrophotography is to transfer the developed toner in two steps. While the principles are the same, the physical properties of the system components differ significantly between primary and secondary transfers, or between primary transfers of first-color toner and second-color toner. The effects of these differences on the transfer fields are quantitatively examined by mathematical analyses.

Introduction
Electrostatic transfer of images from one substrate to another is an important step in electrophotography. A popular technique for this step in color electrophotography is to first transfer the images (toners) developed on a photoreceptor to an intermediate substrate, one color at a time, in the "primary transfer". Then, the accumulated images on the intermediate substrate are collectively transferred to output media in the "secondary transfer". Both transfer steps are based on the same principle. A bias voltage is applied across the multi-layer consisting of the donor, the receiver, the toners, and air-gap, as shown in Fig. 1. A successful transfer requires distributing a large fraction of the applied voltage to the toner layer to be transferred. This is made possible by efficient dielectric relaxation in the receiver and/or the donor, the layers with the largest thickness. While the principles are the same, significant differences exist in the physical properties of the system components involved in these transfer steps. First, the donor in the primary step is an insulating photoreceptor of thickness about 20 µm, whereas in the secondary step it is a semi-insulating intermediate substrate, with good dielectric relaxation, of thickness about 100 µm. Next, the toner layer to be transferred in the secondary step is thicker than that in the primary step (=10 µm) by a factor of 2 to 4. Furthermore, within the primary steps, the transfer of the second- (and third-, fourth-) color toners differs from that of the first-color toners, because of the existence of previously transferred toner layer on the receiver surface, (Fig. 1). The thickness of this "post-transfer" toner layer is comparable or larger than that of the "pre-transfer" toner layer.

The objective of the present work is to quantitatively examine the consequences of the above-mentioned differences by mathematical modeling. These differences have not been explicitly considered in previous modeling works on electrostatic transfer.1-8

Multi-layer Model of Electrostatic Transfer
The configuration at the transfer nip is represented by the one-dimensional multi-layers of Fig.1. The thickness and the permittivity of the k-th layer (k = 1 to 5) are denoted by Lk and εk, respectively. The receiver layer (k = 1) and the donor layer (k = 5, in secondary transfer) are semi-insulators that contain mobile charge with volume densities q1(x1) and q5(x5), respectively, which are functions of position xk. The air gap (k = 3), the post-transfer (k = 2) and the pre-transfer (k = 4) toner layers are insulators that contain no mobile charges. But the toner layers are assumed to have a constant and uniform volume charge density qt. The surface charge density at the interface between receiver and post-transfer toner layer is denoted by Qr, and the corresponding one at the interface between donor and pre-transfer toner layer by Qd. The field, Ek(xk), and the voltage Vk across the layer k, can be expressed in terms of these charge densities, thickness and permittivity, and related to one another using Gauss theorem for the electrostatics. These mathematical expressions are derived in Appendix.
The field at the interface between the pre-transfer toner layer (k = 4) and the donor (k = 5) is denoted as “transfer field”, $E_{tr}$. In order to achieve full transfer, $E_{tr}$ must be greater than the field required for toner detachment. It can be shown (in Appendix) that $E_{tr}$ is related to $V_4$ as,

$$E_{tr} = \frac{(Q_4/2 - C_4 V_4)}{ε_4}$$  \hspace{1cm} (1)

where $Q_4 = q_4 L_4$ is the toner charge density per area and $C_4 = ε_4 / L_4$ is the capacitance of pre-transfer toner layer.

After the bias $V_b$ is applied, the layer voltages $V_k$ change with time due to dielectric relaxation in the layers. The dielectric relaxation of the multi-layer can be treated by two different approaches using the equivalent RC-circuit model or the space-charge transport model. The former model has been described by many authors.\(^2-5\) In the space-charge model\(^1,8,9\) we consider the densities of mobile charge $q_k(x_k)$ into the receiver and/or donor layers are assumed to be adjacent electrode. The injection currents from the electrode with time due to dielectric relaxation in the layers. The proportionality constant $s_k (k = 1 \text{ or } 5)$ specifies the strength of injection at the contact. Note that $s_k$ has the dimension of conductivity.

Starting with the initial conditions and the boundary conditions (in Appendix), an iterative numerical procedure for the continuity equations is used to calculate the time evolution of charge densities $q_i(x_k)$. The fields $E_k(x)$ and the voltages in each layer $V_k$ are determined from Poisson’s equation. Then, the transfer field $E_{tr}$ is calculated from Eq(1).

Transfer Fields, Numerical Results

Examples of numerical results are presented in normalized units listed in Table I. The values of the first four basic units are chosen for convenience to the present application. The values of the other six units follow from their definitions in Table I. The values of the first four basic units are assumed in the examples.

<table>
<thead>
<tr>
<th>Table I: Normalized Units</th>
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<tbody>
<tr>
<td><strong>Length:</strong> $L_o$  \hspace{1cm} \hspace{1cm} \hspace{1cm} \hspace{1cm} (10^{-2} \text{ cm})</td>
</tr>
<tr>
<td><strong>Time:</strong> $t_o$  \hspace{1cm} \hspace{1cm} \hspace{1cm} \hspace{1cm} (10^{2} \text{ sec})</td>
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<tr>
<td><strong>Permittivity:</strong> $ε_o$  \hspace{1cm} \hspace{1cm} \hspace{1cm} \hspace{1cm} (5x10^{13} \text{ F/cm})</td>
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<tr>
<td><strong>Voltage:</strong> $V_o$  \hspace{1cm} \hspace{1cm} \hspace{1cm} \hspace{1cm} (10^{3} \text{ V})</td>
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<tr>
<td><strong>Field:</strong> $E_o = V_o / L_o$  \hspace{1cm} \hspace{1cm} \hspace{1cm} \hspace{1cm} (10^{7} \text{ V/cm})</td>
</tr>
<tr>
<td><strong>Capacitance:</strong> $C_o = ε_o / L_o$  \hspace{1cm} \hspace{1cm} \hspace{1cm} \hspace{1cm} (5x10^{-11} \text{ F/cm}^2)</td>
</tr>
<tr>
<td><strong>Charge density (area):</strong> $q_{t4} = C_o V_o$  \hspace{1cm} \hspace{1cm} \hspace{1cm} \hspace{1cm} (5x10^{-8} \text{ Coul/cm}^2)</td>
</tr>
<tr>
<td><strong>Charge density (volume):</strong> $q_{t} = C_o V_o / L_4$  \hspace{1cm} \hspace{1cm} \hspace{1cm} \hspace{1cm} (5x10^{-6} \text{ Coul/cm}^3)</td>
</tr>
<tr>
<td><strong>Mobility:</strong> $μ_4 = L_4 / t_o E_o$  \hspace{1cm} \hspace{1cm} \hspace{1cm} \hspace{1cm} (10^{-5} \text{ cm}^2/\text{V.sec})</td>
</tr>
<tr>
<td><strong>Injection strength (and conductivity):</strong> $σ_o = q_4 μ_4 = ε_o / t_o$  \hspace{1cm} \hspace{1cm} \hspace{1cm} \hspace{1cm} (5x10^{-11} \text{ S/cm})</td>
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</table>

Primary Transfers

Figure 2 shows examples of the time evolution of transfer fields $E_{tr}$, calculated for typical primary transfers of second-color toners, with the first-color toners already on the receiver. The donor is a discharged insulating photoreceptor. The parameter values are chosen as: $L_1 = 1, L_2 = L_3 = L_4 = 0.1, L_5 = 0.2; ε_1 = 1, ε_2 = ε_4 = ε_5 = 0.5, ε_3 = 0.2; q_{t4} = -4$ and $V_b = 1$, all in normalized units of Table I. The conduction and injection properties of the receiver layer are specified by $q_{i1}, s_1$ and $μ$ values.

The $E_{tr}$ is found to approach an asymptotic value that is independent of the values of transport parameters, $q_{i1}, s_1$ and $μ$. With large $q_{i1}$ (>0.1) and/or large $s_1$ (>0.1), the approach is complete in a few tens of units of time $t_o$ (Table I). However, if the nip time is limited, $E_{tr}$ can be significantly smaller with smaller $q_{t}$ and/or $s_1$.

![Figure 2](ClrTrans_040506/3.png)
independent roles on the transfer field. Both $q_i$ and $s_i$ determine the supply of charge needed for dielectric relaxation by complementing each other, while the mobility determines the time needed for the relaxation.

The dependence of $E_{tr}$ (the asymptotic values) on the thickness of post-transfer toner layer $L_2$ in primary transfer is shown in Fig. 3 for a receiver with good dielectric relaxation, ($q_i=1, \mu = 1$ and $s_i=1$). The curve with $L_2 = 0$ corresponds to the transfer of the first-color toners. As the thickness $L_2$ increases, it requires longer time for the transfer field to become positive (required for the detachment of negative toners), and the asymptotic value is smaller.

![Figure 3. Primary transfer field $E_{tr}$ vs. time, with thickness of post-transfer toner layer $L_2$ varied.](image)

The results of similar calculations are summarized in Fig. 4 by plotting the asymptotic values of $E_{tr}$ as functions of post-transfer toner layer thickness $L_2$ and toner charge density $q_t$. The transfer fields are seen to decrease linearly as the thickness of post-transfer toner layer increases. This indicates that if the bias voltages and the nip dwell time remain the same, the second-color transfer (and the following ones) can be less complete than the first-color transfer. The results in Fig. 4 appear to suggest a merit for lower toner charge density. However, it should be noted that the required detach field for lower charge toners can be larger.10,11

Secondary Transfers

In secondary transfers, the donor layer ($k = 5$) becomes as semi-insulating and as thick as the receiver layer ($k = 1$). In addition, the (pre-transfer) toner layer thickness $L_4$ is 2 to 4 times thicker than that in primary transfers, (but $L_2 = 0$). Figure 5 shows the effects of intrinsic charge density $q_{i5}$ and injection strength $s_5$ of the donor on the growth of transfer field. The donor thickness $L_5$ is assumed to be the same as that of receiver, and the toner layer thickness $L_4$ (multi-color) is twice that of the primary (single color). A first-color primary transfer is also shown by a dashed curve for comparison. The transfer field is seen to need some time to become positive, and the asymptotic value is smaller than that for the primary. The charge transport properties of donor, $q_{i5}$ and $s_5$, have significant effects on the size of $E_{tr}$.

![Figure 4. Asymptotic values of primary transfer field vs. post-transfer toner layer thickness, for three values of toner charge density $q_t$.](image)

![Figure 5. Time evolution of transfer fields in secondary transfer. Intrinsic charge density $q_{i5}$ and injection strength $s_5$ of donor varied.](image)

Figure 6 summarizes the results of similar calculations. The asymptotic transfer fields are shown as the toner layer thickness $L_4$, charge density $q_t$, and the transport properties of donor ($q_{i5}$ and $s_5$) are varied. The semi-insulating nature of donor in secondary transfer is seen to have a merit of increasing the transfer field. However, this is countered by the increase in the toner thickness $L_4$ (due to multi-color images). The smaller the toner charge density $q_t$, the larger the transfer field, as in the primary transfer (Fig. 4).
Discussion and Conclusions

Corresponding calculations of transfer fields with the RC-circuit model are also carried out (in Appendix). The features of transfer fields in multi-color primary transfers and secondary transfers are found to be essentially similar to those obtained by the space-charge model, shown in Figs. 3 to 6. Thus, independent of whether the RC-circuit model or the space-charge model is used for analyses, it can be concluded that: (1) In primary transfers, the transfer fields for the second (or higher) color becomes weaker than that for the first color as the thickness of the post-transfer toner on the intermediate substrate increases (Fig. 4); (2) In secondary transfers, the transfer field is enhanced by the donor being a semi-insulator, but weakened by the larger thickness of (multi-color) toners to be transferred (Fig. 6); and (3) Smaller toner charge density increases transfer field (Figs. 4 and 6). However, it should be noted that toners with smaller charge density may require a larger detach field.10,11

The RC-circuit model has the advantage of simplicity and familiarity in specifying the electrical property of the layers by their resistances (or conductivity). However, as demonstrated with Fig. 2, conductivity is not sufficient for the determination of transfer field, and the characterization of dielectric relaxation in general. Furthermore, because the electrical contacts to the receiver or the donor (and semi-insulators in general) are not always Ohmic and hence, the resistance is often not a well-defined quantity.

In contrast, the space-charge model specifies the electrical properties in terms of intrinsic charge density qi, charge mobility μ and injection strength s at the contact. While the resistance is an intrinsic material property, the injection strength s is determined by the nature of interface between two layers. It depends on the fabrication condition and can change with usage. Furthermore, because the intermediate substrate serves as a receiver in primary transfers and as a donor in secondary transfers, the polarity dependence of charge injection and transport makes significant differences. As illustrated in Fig. 7, with negative toners (for example), injection and transport of positive charges are needed for the primary, but those of negative charges are required for the secondary. Because resistance does not specify the charge polarity, it is not sufficient for electrical characterization of transfer media. The transfer fields are seen to have strong dependence on the size of injection, especially for materials with small intrinsic charge density qi, and/or for limited nip time due to higher process speeds (Figs. 2 and 5).

Appendix (available on request from the author)

References

Biography

Inan Chen received his Ph.D. from the University of Michigan in 1964, and worked at Research Laboratories of Xerox Corp. in Webster, NY, from 1965 to 1998. Currently, he is a consulting scientist at Quality Engineering Associates (QEA) Inc. and others, specializing in mathematical analyses of physical processes, in particular, related to electrophotography. Contact at inanchen@aol.com.