Consideration of the Counter Charge Traveling Distance on the Charge Transport Equilibrium Mechanism with a Dynamic Procedure

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要旨

電子写真の歴史において二成分磁気ブラシ現像法は，その品質，耐久性，および現像特性の制御性の高さから，多くのカラー MFPおよびプロダクションプリンターで採用されてきた。栗田が提案した電荷輸送平衡メカニズムは，電子写真の二成分現像法における現像特性の解析モデルとして有用であり，多くのMFP設計に適用されている。このモデルでは，カウンターチャージの移動距離を定数として扱い，その値を実験的に推定している。著者は，拡散モデルと電荷移動度モデルを適用することにより，カウンターチャージ輸送プロセスの反復計算を試みた。各計算モデルにおいて，現像特性は所定時間経過後緩やかな時間依存性を示し，電荷輸送平衡メカニズムが概ね支持されているという結果が得られた。

拡散モデルは，DCバイアス電圧が印加された現像条件に適合した。「トナー供給制限」の条件を除いて，電荷輸送平衡メカニズムが適用可能である。電荷移動度モデルは，ACバイアス電圧を重畳した現像条件に適合した。この場合，現像時間が交流電圧の振幅などによって決定されるカウンターチャージの通過時間よりも長い場合，電荷輸送平衡メカニズムが適用可能である。これらの結果は，経験的ノウハウを解析的理解に置き換え，技術的知識の伝承に役立てるという価値をもたらす。電子写真技術の向上のために，更なる応用が期待される。

Abstract

In the history of the electrophotography, two-component magnetic brush development method has been adopted in many color MFPs and production printers because of its quality, durability, and controllability in developing characteristics. The charge transport equilibrium mechanism proposed by Kurita is useful as an analysis model of development characteristics in two-component development method of electrophotography and has been applied in many MFP designs. In this model, the traveling distance of the counter charge is treated as a constant, and its value is estimated experimentally. The author tried an iterative calculation of the process of counter charge transport by applying a diffusion model and an electric charge mobility model. In each calculation model, the development characteristics showed a gradual time dependence after a lapse of a predetermined time, and the results obtained that the charge transport equilibrium mechanism was generally supported.

The diffusion model met the developing condition that DC bias voltage was applied. The charge transport equilibrium mechanism can be accepted except the condition under the 'limitation of toner supply'. The electric charge mobility model met the developing condition that AC bias voltage was superimposed. In this case the charge transport equilibrium mechanism can be accepted if the developing time is longer than the transit time of counter charge which is determined by amplitude of AC voltage and so on. These results provide the value of replacing empirical know-how with analytical understanding and helping to transfer technical knowledge. Further applications are expected for improving electrophotographic technology.

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1 Introduction

In the history of the electrophotography, two-component magnetic brush development method has been adopted in many color MFPs and production printers because of its quality, durability, and controllability in developing characteristics. Several important theories and models helped in designing developing systems and controlling algorisms for image stabilization. Kurita's Charge transport equilibrium model [1] is one of the useful models for analyzing experimental data. Equation (1) shows Kurita's original charge transport equilibrium model determining developed toner charge Q;

$$Q = \frac{-\varepsilon_0 V_0}{d_s/k_s + d_t/k_t + d_c/k_c\theta} \tag{1}$$

where V_0 is given potential difference, θ is speed ratio between developing roller and photoconductor, and d_s/k_s, d_t/k_t and d_c/k_c are equivalent thickness of the photoconductor, developed toner layer and the counter charge. In this model, developability is dominated by the counter charge thickness and θ.

Equation (2) shows Hattori's revised charge transport equilibrium equation (2019) [2]. In this equation, the term of the counter charge thickness is modified considering relative movement of developer from the viewpoint of developed photoconductor.

$$Q = \frac{-\varepsilon_0 V_0}{\frac{d_s}{k_s} + \frac{d_t}{k_t} + \frac{d_c}{k_c \cdot |\theta| \cdot (1 + |\theta - 1|)}} \tag{2}$$

Fig. 1 refers above model [2] showing the counter charge is condensed or diluted to $1/|\theta|$ and $|\theta\text{-}1|$ is ejected to the vertical direction. In this figure the distance of the counter charge is constant.

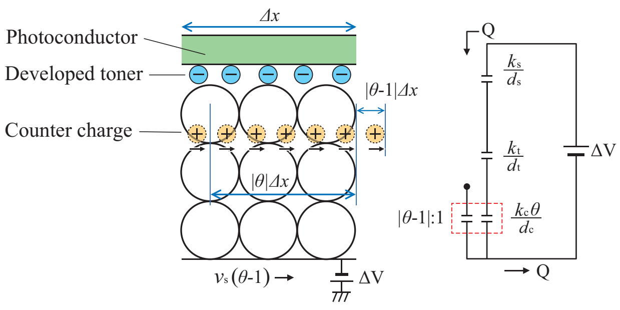

Fig. 1 Schematic illustration and equivalent circuit of the revised charge transport equilibrium model at the condition of 0<θ<1.

Fig. 2 shows comparison between experimental results and the calculated results reported in the author's previous paper [2]. Equation (1) and Equation (2) can meet good correlation with experimental results by estimating some constant value on the term including 'counter charge'. However, there is no suggestion in these models why or how the counter charge is driven to the balanced position. Okada [3] suggested a useful reference as a mathematical solution for both IMB (Insulative Magnetic Brush) and CMB (Conductive Magnet Brush) development method by focusing conductivity of the magnet brush. In this study, the author focused the IMB method and applied a numerical, iterative solution for toner deposition and counter charge transportation to understand the mechanism that the counter charge term seems to be a constant.

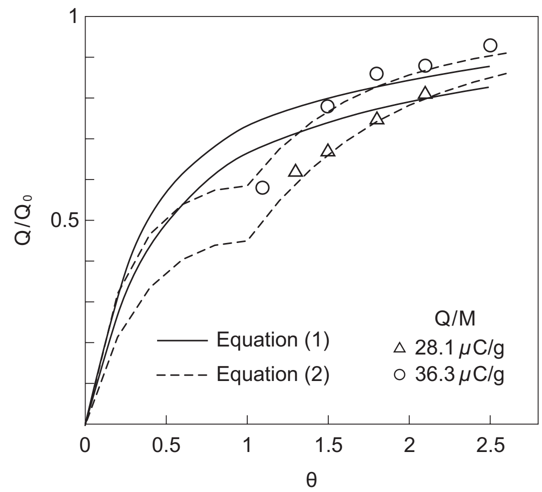

Fig. 2 Comparison between experimental results and the calculation; solid lines are by Equation (1) and dotted lines are by Equation (2).

2 Charge transport model and calculating method

A calculation model is shown in Fig. 3. It is a 'multi-layered model' consists of developer layer, air gap, developed toner layer and photoconductor layer, where developer layer including counter charge is divided in n sublayers (L_1, $L_2 \cdots L_n$) to reproduce counter charge distribution. At the step 1, developed toner charge Q_t and newly generated counter charge in the top sub-layer of the developer ΔQ_{dn} are calculated so as the electric field in the imaginary air gap layer to be zero else toner density in the top sub-layer to be empty. ΔQ_{dn} is condensed or diluted from Q_t by Equation (2);

$$\Delta Q_{dn} = \frac{Q_t(t) - Q_t(t - \Delta t)}{|\theta|(1 + |\theta - 1|)} \tag{3}$$

At the same time, amount of counter charge transport among neighboring sub-layers is calculated by the determined model. After Δt, at the step 2, electric field in all sub-layer are re-calculated on the basis of the new charge distribution calculated at the step 2. Step 1 and step 2 are alternately repeated.

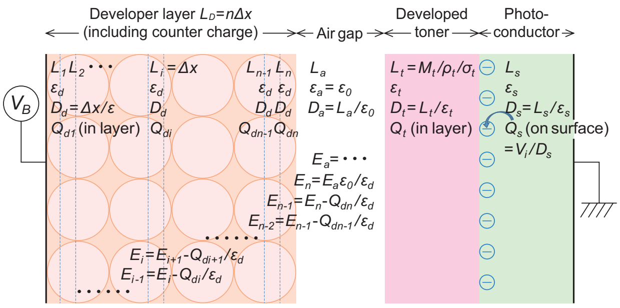

Fig. 3 Iterative calculation model by alternating development and charge transport.

Two types of charge transport model were tested: the Fick's laws of diffusion and the electric charge mobility model. By Fick's laws, counter charge density Q_{di} (t) in sublayer L_i is expressed in the following Equation (4);

$$Q_{di}(t) = Q_{di}(t-\Delta t) + \delta\{Q_{di+1}(t-\Delta t) - Q_{di}(t-\Delta t)\} - \delta\{Q_{di}(t-\Delta t) - Q_{di-1}(t-\Delta t)\} \quad (4)$$

where δ is the diffusion coefficient. This model assumes the counter charge transportation is dominated by mechanical dispersion such as vibration or collision rather than electrostatic force.

In another model, the counter charge transportation is dominated by electrostatic force received from the electric field;

$$\frac{\Delta Q_{di}(t)}{\Delta t} = \mu Q_{di}(t-\Delta t) E_i(t-\Delta t) \quad (5)$$

where μ is the counter charge mobility and E_i is the electric field in the i-th sublayer of the developer layer.

List of the parameters for calculation is as follows;

- Developer layer thickness $L_D = 0.5$ mm
- Number of divisions of the developer layer $n = 40$
- Imaginary Air gap layer $L_a = 0.1\ \mu$m
- Packing ratio of toner layer $\sigma_t = 0.5$
- Specific gravity of toner $\rho_t = 1000$ kg/m^3
- Photoconductor layer thickness $L_s = 25\ \mu$m
- Developing bias voltage V_B = -500 V
- Latent image potential on photoconductor V_i = -100 V
- Toner charge per weight q/m = -30 μC / g
- Permittivity of the air gap (vacant) $\varepsilon_0 = 8.85\times10^{-12}$ F/m
- Relative permittivity of the developer layer $\varepsilon_d = 2.5$
- Relative permittivity of the toner layer $\varepsilon_t = 2.0$
- Relative permittivity of the photoconductor $\varepsilon_s = 2.7$
- Counter charge mobility $\mu = 1.0\times10^{-7}$ m^2/ Vs

Unit time Δt is tuned as $\mu E_n(0)$ doesn't exceed $L_D/n/\Delta t$. Development efficiency η is evaluated;

$$\eta = \frac{Q_t}{Q_0}$$
$$Q_0 = \frac{-\varepsilon_0(V_B - V_i)}{L_s/\varepsilon_s + L_t/\varepsilon_t} \quad (6)$$

3 Results and discussion

3. 1 Diffusion-model-based analysis

Fig. 4 shows an example of the result supposing charge transport was given by the Fick's laws of diffusion at the condition δ = 0.1 and θ = 0.25. In case that diffusion model was supposed, counter charge generated at L_{40} gradually moved slowly and kept stagnation around the photoconductor side.

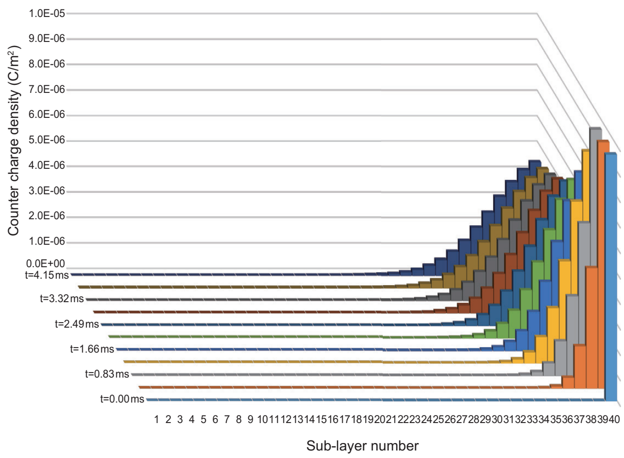

Fig. 4 Calculated result of the counter charge distribution in the developer layer by applying diffusion model (at θ = 0.25, δ = 0.1).

Fig. 5 is the time dependence of development efficiency by supposing the diffusion model. The figure shows rapid increment of efficiency from t = 0 to 0.1ms and nearly static state after that. During the period of above rapid increment, the calculation result indicated a state like 'limitation of toner supply'. Even if E_a was not canceled to zero, toner density at L_{40} became empty and development did not progress until toner was dispersed from the neighboring sub-layer.

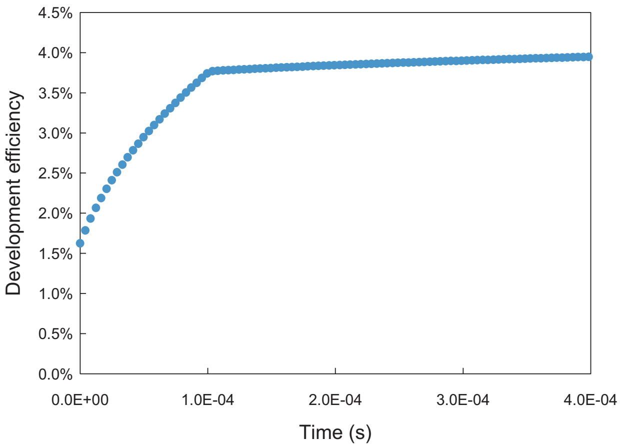

Fig. 5 Calculated result of development efficiency by applying diffusion model (at $\theta = 0.25$, $\delta = 0.1$).

Fig. 6 shows effect of θ at the diffusion model calculation. By giving sufficient θ, 'limitation of toner supply' could be avoided. Anzai et al. [4] suggested that toner to develop latent image was provided from the uppermost carrier layer, and that mechanical force by magnetic brush should be included in developing forces acting on toner. The diffusion model seems to correspond to their investigation in case of IMB system that DC bias voltage is applied.

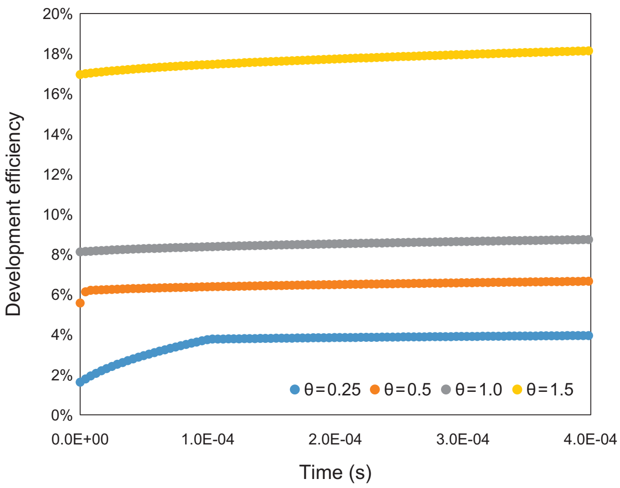

Fig. 6 Calculated result of development efficiency by applying diffusion model (at $\theta = 0.25$, 0.5, 1.0 and 1.5, $\delta = 0.1$).

3.2 Electric-charge-mobility-model-based analysis

Fig. 7 shows another example of the result supposing charge transport is given by electric charge mobility model. Counter charge generated at the photoconductor side of the developer layer was transported to the developing roller side in about 2ms and was stayed around the neighboring area of the developing roller. Fig. 8 shows a corresponding result of development efficiency. At the start of development, 'limitation of toner supply' was observed from t=0 to 0.4ms, consecutively from t=0.4ms to 2.2ms, developing efficiency was increased according to counter charge transport form the photoconductor side to the developing roller side, and finally developing efficiency became constant. The result can be understood that transport of counter charge induces toner deposition and that it requires 'transit time' for developing property to be in the stable situation. The 'transit time' may be a factor for the process speed limitation of the system.

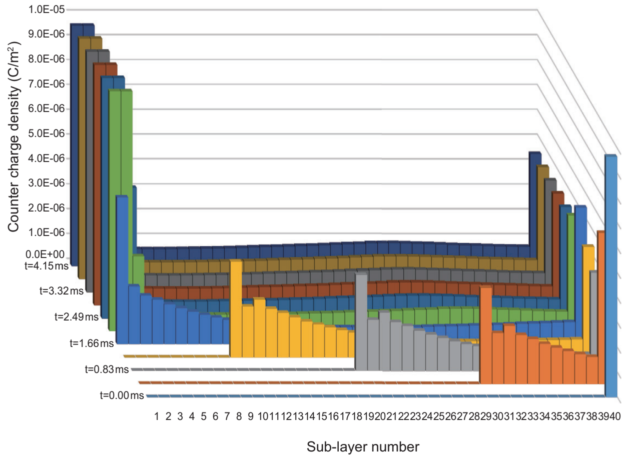

Fig. 7 Calculated result of the counter charge distribution in the developer layer by applying electric charge mobility model (at $\theta = 0.25$, $\mu = 1.0 \times 10^{-7}$ m²/Vs).

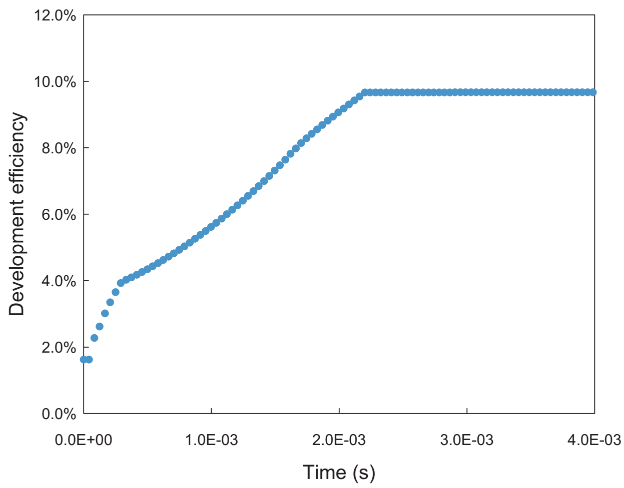

Fig. 8 Calculated result of development efficiency by applying electric charge mobility model (at $\theta = 0.25$, $\mu = 1.0 \times 10^{-7}$ m²/Vs).

Fig. 9 shows effect of θ at the electric charge mobility model calculation. As can be seen from the figure, developing efficiency was relatively increased by applying larger θ but it does not have effects to accelerate the developing speed. On the contrary, Fig. 10 shows effect of μ. By giving the larger μ, the developing efficiency reached to the saturated level in a shorter time, but the saturated levels were the same.

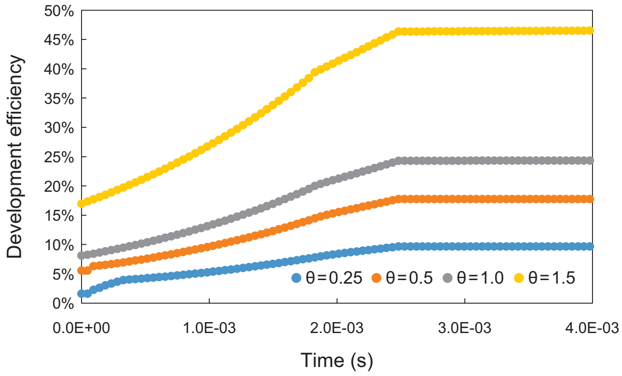

Fig. 9 Calculated result of development efficiency by applying electric charge mobility model (at θ=0.25,0.5,1.0 and 1.5, μ=1.0×10^{-7} m^2/Vs).

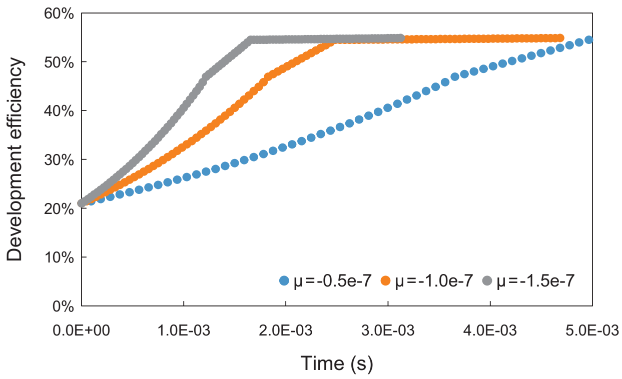

Fig. 10 Calculated result of development efficiency by applying electric charge mobility model (at θ = 1.7, μ = 0.5×10^{-7}, 1.0×10^{-7} and 1.5×10^{-7} m^2/Vs).

In case of two-component development method applying AC bias voltage superposition, AC amplitude is considered as a parameter of the counter charge mobility. In actually, counter charge is a part of charge on the carrier surface with opposite polarity to toner. Counter charge is appeared when a toner particle is deposited from the carrier surface and transferred and disappeared when another toner moved from neighbor onto there. There exist many kinds of barriers or traps for toner transition through the developer layer. AC bias generates an alternating electric field in the developer layer and is thought to affect the toner to overcome barriers and traps resulting counter charge transport. Fig. 11 shows experimental data of developing property under various condition of AC bias superposition reported by the author in 1997 [5]. In this figure, *M/A* (mass of toner per unit area) was increased by applying AC bias superposition from 0 (=DC only) to 1.0 $kV_{P\text{-}P}$ and saturated at 1.0 $kV_{P\text{-}P}$ and more. It is understood that the counter charge mobility was increased by AC bias superposition and the transit time came up at the developing time when AC bias became 1.0 $kV_{P\text{-}P}$.

In rough approximation, supposing the process speed limitation of the single-headed two-component development method utilized in color MFPs to be around 500 mm/s and contact width between magnet brush and photoconductor to be 1mm, developing time is calculated as 2.0 ms. Developing property should be saturated until the end of the developing region if the unit were designed with sufficient robustness. When the developer layer thickness is 0.5 mm and developing bias is 500 V, mobility of the counter charge is approximated to be 5×$10^{-7}$$m^2$/Vs. It is as same order as mobility of organic semiconductor.

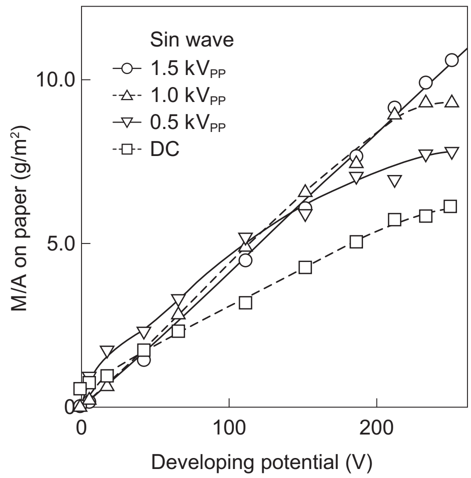

Fig. 11 Experimental result of the change in development property depending on AC bias superposition reported in [5]. *M/A* (mass of toner per unit area) was increased by applying AC bias superposition from 0 (=DC only) to 1.0 $kV_{P\text{-}P}$ and saturated at 1.0 $kV_{P\text{-}P}$ and more.

4 Conclusion

Although the charge transport equilibrium model is well-known as a useful model for analyzing experimental data of the two-component development method, there was no discussion why and how the counter charge layer was determined. In this study, an iterative calculation method was applied to consider the process of counter charge transport. A diffusion model and an electric charge mobility model were discussed. The diffusion model met the case that DC bias voltage was applied. The charge transport equilibrium mechanism can be accepted except the condition under the ‘limitation of toner supply’. The electric charge mobility model met the case that AC bias voltage was superimposed. In this case the charge transport equilibrium mechanism can be accepted if the developing time is longer than the transit time of counter charge which is determined by amplitude of AC voltage and so on.

Although two-component development method has been applied to many commercial products and has contributed to progress in speed and quality of electrophotographic process, few analytic investigations have been presented recently. In this paper, two-component development method was discussed by utilizing a charge transport model in multi-semi-conductive-layer. Such a model is worthful to improve technical knowledge from empirical know-how to analytical understanding. Further applications are expected for improving electrophotographic technology.

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Acknowledgment

Dr. Inan Chen, former in Xerox Corporation, gave lectures and consultations of physics and mathematics from 1999 to 2009 concerning electrophotographic process and materials including multi-layered model for charge transport calculation. The author expresses cordial gratitude for his worthful instructions.

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