Technology for Electrostatic Separation of Charged Toner Particles with Different Sign by Utilizing Electrostatic Traveling Wave

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Abstract

The author has studied toner transport utilizing electrostatic traveling wave with high-speed photography, measurements of toner charge distributions, and numerical simulations. In this study, the author has concentrated on the toner cloud above the main transport stream. The mechanism of the toner cloud formation has been identified, and a method to separate the correct sign toner from the wrong sign toner particles utilizing the mechanism has been developed. For the fewer toner particles and a lower speed toner transport, we used high-speed photography to observe an arch-shaped toner cloud above the transport. Using a simplified model, we have found that such an arch-shaped toner cloud is formed by the effect of air-drag. On the other hand, in the development system conditions such as a higher toner concentration and a faster speed toner transport, the arch-like cloud becomes dense because of the effect of the electrostatic attraction force. The author has proposed that the cloud comprises the same number of toner particles of both signs, and has designed toner separation and re-charging system using vertical toner transporting.

Introduction

Since the first development of the technology of particle transport in an electrostatic traveling wave by Masuda et al. [1] (Figure 1), many electrophotography studies have been performed using this technique [2][3]. While past studies focused on the amount of transported toner, for further development of toner systems it is important to obtain appropriate toner conditions. For example, techniques utilizing the traveling wave for the separation of particles of different sizes were studied by Kawamoto [4]. Furthermore, it is important to obtain an appropriate toner charge distribution to avoid the development of fog.

In electrostatic toner transport, a toner cloud is present above the traveling wave (Figure 2). We studied the cloud formation process to eliminate the wrong sign toner. For this study, we used examinations of high-speed movies, numerical simulations of toner motion with the distinct element method (DEM), and toner charge distribution measurements with the E-spart analyzer. Appropriate toner charge conditions were obtained by separating the wrong sign toner.

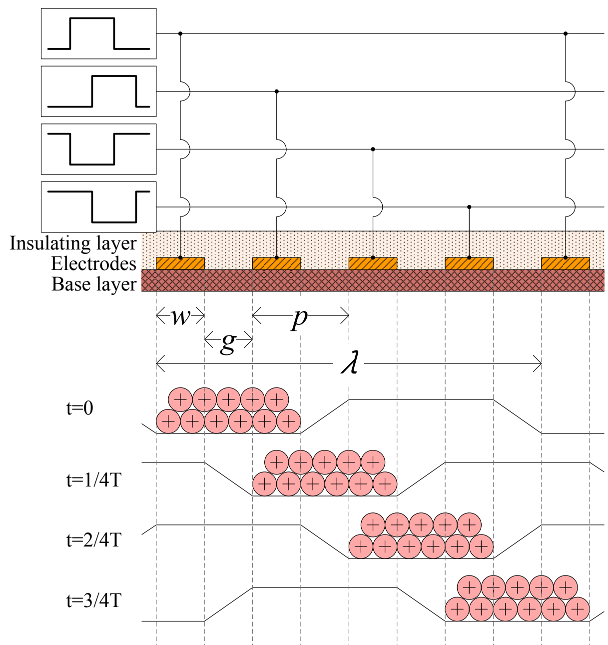

Figure 1. Schematic illustration of traveling wave transport

Table 1 List of simulation parameters

Width of Electrodes	0.1 mm
Gap of Electrodes	0.1 mm
Number of Phases	4
Wave Form	Rectangle
Applied Voltage	+/- 200 V
Frequency	50Hz

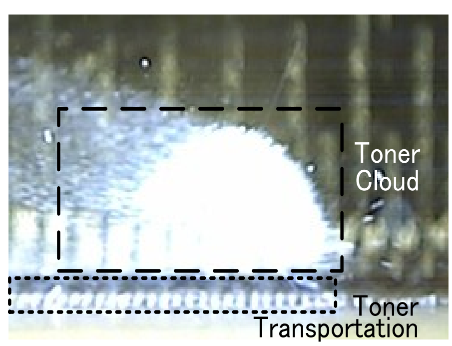

Figure 2. Image of toner transportation taken by high speed camera

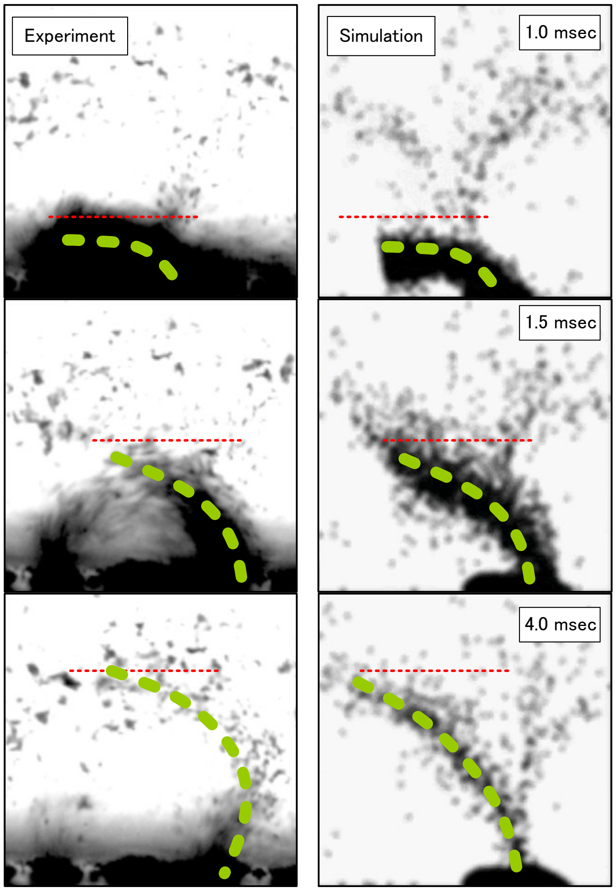

Figure 3. Time series of toner motion. Left: High speed camera. Right: Numerical simulation.

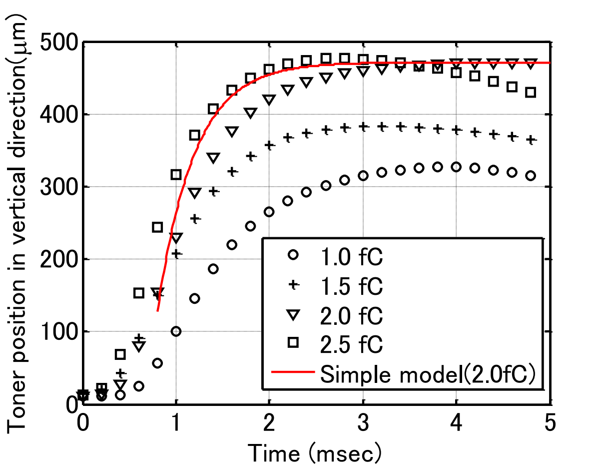

Figure 4. Transition of toner position in vertical direction (simulation and simple air-drag model)

Materials and Methods

Electrostatic Particle Transport

Electrostatic particle transport uses parallel cyclic electrodes covered with an insulating layer. Rectangular waves or sinusoidal waves with four or more different phases are applied on each electrode to give rise to the electrostatic traveling wave. Particles are attracted to the electrical potential of the opposite sign, and move with the electrostatic wave (Figure 1). The conditions specified in Table 1 were used for this study.

Numerical Simulation

We modeled the toner motion using a numerical simulation method called the distinct element method (DEM) with electrostatic field calculation by the finite element method (FEM). The motion of a toner is governed by the following equation:

$$m\frac{d^2 x_i}{dt^2} = \sum_{i \neq j} F_{ij} - 6\pi\eta r v_i + qE + mg$$

where m is the mass, x is the position, η is the viscosity of air, r is the radius, v_i is the velocity, q is the charge, E is the electrostatic field calculated by FEM, and g is the gravitational acceleration. The contact force F_{ij} between the particles i and j is given as follows:

$$F_{n,ij} = K_n \Delta x_{n,ij} + D_n \frac{\Delta x_{n,ij}}{\Delta t}$$

$$F_{t,ij} = \min\left[\mu F_{n,ij}\ ,\ K_t\left(\Delta x_{t,ij} + \Delta\phi_{ij}\right) + D_t \frac{\Delta x_{t,ij} + \Delta\phi_{ij}}{\Delta t} \right]$$

where K is the spring constant, D is the viscosity constant, Δx is the relative displacement of the toner particles i and j, $\Delta\varphi$ is the relative rotational displacement, μ is the friction coefficient, and Δt is the calculation time step.

High-Speed Movie

We recorded high-speed movies of electrostatic toner transport, taking 10000 frames per second. In the recording process, the source was placed at the back of the transport to enable the use of the transmitted light with the toner appearing as a black shadow. The frequency of the applied voltage on the electrode is 50 Hz to take one-shot toner motion.

Results and Discussion

Toner Cloud Forming Process

We first investigated fewer toner and one-cycle transport using a high-speed movie and numerical simulations to examine the toner motion in the cloud forming process. In these conditions, an arch-shaped toner cloud is observed both in the experimentally obtained movie and in the numerical simulations results (Figure 3). The arch shape differs from those of the equipotential line or of the electrical flux line, implying that the formation of the arch is not driven by the electrical force effects.

The arch may be formed by the air-drag force. Therefore, we created a simple model that contains only the instantaneous acceleration and air drag. The attenuation length of the electric field generated by cyclic electrode is almost $\lambda/2\pi$ where λ *is* wave length of electrostatic wave [2]. In our simple model, the toner is accelerated closer than $\lambda/2\pi$ and farther than $\lambda/2\pi$ because of the air-drag that acts on it. The model is described as follows:

$$\begin{bmatrix} m\dfrac{dv}{dt} = -6\pi\eta r v \\ \left(x_0 = \dfrac{\lambda}{2\pi}, \dfrac{1}{2} m {v_0}^2 = q\Delta V \right) \end{bmatrix}$$

$$\rightarrow \begin{bmatrix} x(t) = v_0 \tau (1 - e^{\frac{-t}{\tau}}) + x_0 \\ v_0 = \sqrt{\dfrac{2q\Delta V}{m}}, \tau = \dfrac{m}{6\pi\eta r} \end{bmatrix}$$

where $x0$ is the end point of the instantaneous acceleration estimated from wavelength of electrostatic wave λ, ΔV is difference between the electrical potential values at $x0$ and at the substrate surface, and $v0$ is the toner velocity at point $x0$ *estimated from* ΔV.

Figure 4 shows the comparison of the toner positions obtained using this model and those found in the simulation. The model is consistent with the toner motion found in numerical simulation, and shows that the arch-shape cloud is because of the deceleration effect of air-drag.

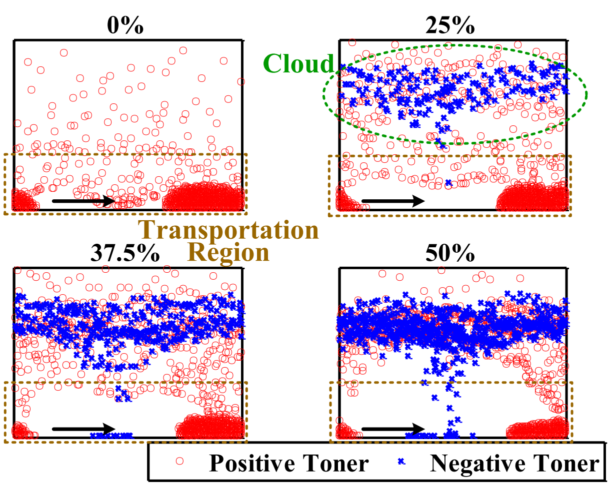

Figure 5. Toner position for different negative toner ratios in particle simulation

Charge Distribution in Toner Cloud

First, we performed the simulations of toner transport with different fractions of the wrong sign toner to elucidate the effect of the wrong sign toner (Figure 5). Without the wrong sign toner (left-top), the arch-shape cloud does not grow and soon vanishes. However, the arch-shape toner cloud becomes dense with increasing density of the wrong sign toner, implying that the presence of the wrong sign toner gives rise to the dense static cloud and shows that a large fraction of the wrong sign toner is located in the cloud and not in the transportation area. This means that we can separate the wrong sign toner by removing the toner cloud.

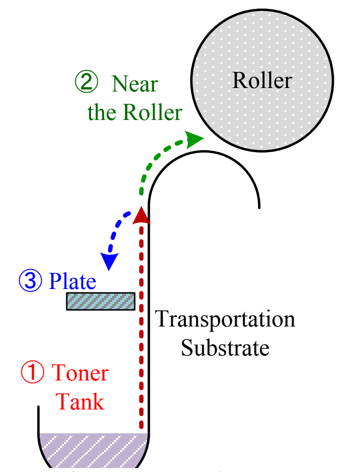

Figure 6. Schematic View of the Experiment

Next, we studied the cloud conditions by measuring the toner charge distribution using the E-spart analyzer by Hosokawa Micron. The experimental setup is shown in Figure 6. The toner is transportation vertically and the toner cloud drops from substrate due to gravity and is caught by the plate. We measured the toner charge distribution (1) before transportation, (2) after transport to the top of the substrate, and (3) dropped from the substrate and caught by the plate. Furthermore, we calculated toner charge distributions using simulations (1), and compared the simulated toner distributions of (1) all of the toner, (2) the toner in the transportation region, and (3) the toner in the cloud.

Following transport, the toner contains less wrong-sign toner (Figure 7), with this feature observed both in the experimentally obtained charge distribution of experiment and in that of simulation. No fog development is expected to arise from the toner charge distribution measured after transport.

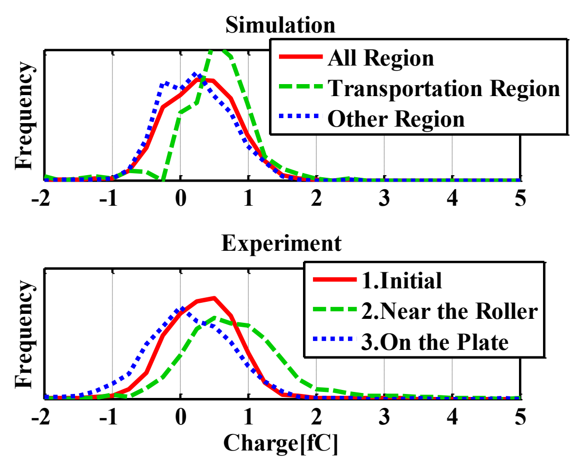

Figure 7. Toner charge distribution before and after charge separation as obtained by simulation and experiment

Mechanism of Charge Separation

The mechanism of separation of wrong sign toner fraction is as described below.

The toner lifted by the electrostatic force above the transport substrate is compressed into an arch-like cloud by air drag. In the presence of the wrong sign toner, the toner particles with different signs are connected by the attractive electrostatic force in the cloud.

The connected toner experience a weak electric force because of the weak total charge value, and experiences a large air-drag force because of the large cross-section. Because of the small charge and the subsequent lack of an electric driving force, toner particles cannot be transported because of lack of electric driving force over the air drag, and therefore remains in the same places. This is the same phenomenon as that found for the large size or weakly charged toner's motion called the asynchronous mode [5]. Therefore, the dropped toner cloud contains the same absolute charge of toner particles with both sign. The content of the wrong sign toner decreases faster than that of the correct sign toner.

Development System

Furthermore, the experimental setup is used for development of new systems. For example, we can also remove the toner catching plate, because there is no need to catch the toner. Then, the dropped toner returns to the toner tank, and is transported twice by the electrostatic transport. In the transport process, wrong sign or weakly charged toner particles are charged by triboelectric charging, and we can use all of the toner obtained by such recharge process.

Conclusion

We studied the toner cloud forming process above the electrostatic toner transport and determined the effect of toner charge separation process.

We also designed a development system using this mechanism for vertical toner transport to drop the cloud into the toner tank, with the weakly charged toner charged by triboelectric effect with the substrate in the transport process.

References

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Author Biography

Yasuhiro MARUYAMA received his B.S. degree (2005) and M.S. degree (2007) in Particle and Astrophysical Science from School of Science / Graduate School of Science, Nagoya University, Japan. He joined Brother Industries, Ltd. in 2007 and has engaged in the research of electrophotography. He is working on numerical simulation of particle dynamics, electromagnetism and thermodynamics.