The Charging Characteristics of Fine Particle Layers with Corona-Charge

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Abstract

An investigation was carried out on the factors determining the corona charging characteristics of 200µm-thick particle layers consisting of micron-order insulative fine particles. When particle layers were charged using a corona charging device with a grid electrode, the surface potential of the particle layers reached the grid potential in a low grid potential range (range A). In a potential range above the range A (range B), however, the surface potential of the particle layers can no longer reached the grid potential. In this range, a pulsed electric current was observed with an ammeter connected to the conductive plate supporting the particle layers. For both range A and B, the charges from the device existed only on the particle layer surface, and therefore, the charge quantity of the particle layer was approximately proportional to the surface potential. These results led us to infer that in range B discrete small discharges occur in the air-filled spaces between the particles. These discharges were caused by the electric field within the particle layer generated by the charges adhering to the particle layer surface. The relaxation caused by these discharges determines the maximum charge quantity. In this paper, we explain the charging rate and a model for the electric relaxation phenomenon.

Introduction

Electrostatic motion control of charged particles is commonly used in a wide variety of areas, because the electrostatic force becomes dominant when the particles are in a micron size order. In the field of electrostatic precipitations, the electrical characteristics of a charged isolated fine particle by corona charge have been researched for a long time[1]. With regard to particle layers formed by fine particles, although there have been some reports[2~3] about them, many points remain unclear. Accordingly, we investigated the charging characteristics of particle layers formed by micron-order insulative fine particles about 200µm-thick, charged with a corona charging device. In this paper, we explain results on the factors determining the maximum charge quantity of particle layers and the charging rate. A simplified method is also presented to know the charge density distribution in a particle layer.

Experimental Methods

Figure 1 shows the schematic of the experimental apparatus. A 200µm-thick layer was formed with particles on a 15 x 20mm^2 grounded conductive plate set on a moving stage. The particles are spherical and have 5µm-diameter. The particle layer is corona-charged, then the surface potential is measured. After that the charge density distribution in the depth direction or the total charge quantity within the particle layer was measured. In the measurement of the charge density distribution, a conductive adhesive tape connected to an electrometer is attached to the particle layer surface. After the measurement, the same procedure was repeated. In the total charge measurement, the charge quantity is measured with the electrometer connected to the conductive plate when all the particles were sucked into a nozzle at one time. The charging device has a grid electrode, and they can be set at optional potential.

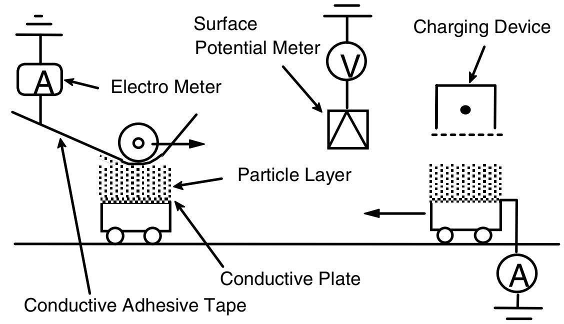


Figure1. Schematic diagram of experimental apparatus

Experimental Results

Surface Potential and Charge Density Distribution of Particle Layers on a Conductive Plate

Figure 2 shows measurement results of the surface potential of a particle layer with changing grid potential. When the absolute grid potential is below 1000V, the surface potential of the particle layer is equal to the grid potential. Over –1000V, the surface potential no longer approach the grid potential, and at –1600V, the surface potential take the maximum value of -1370V then slightly decrease. Over –1000V, a pulsed current was observed through the conductive plate under the particle layer.

Figure 3 shows the charge density distributions within the particle layer when the grid potential is –800V and –1800V. In both conditions, charges exist down to a depth of 40μm from the surface layer, even though a pulsed current is observed in the latter case. We recognize that most of the charges exist in the surface layer because the unevenness of the particle layer surface is about 20μm.

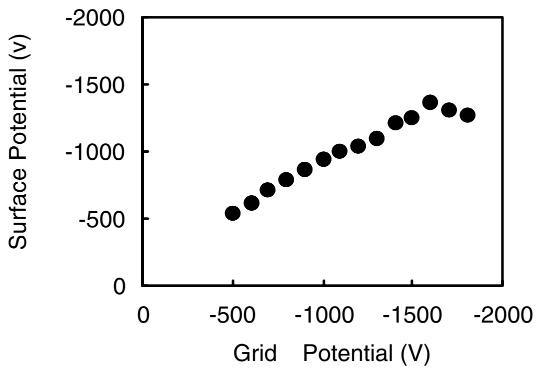


Figure 2. Relationship between the grid potential and the surface potential of the particle layer

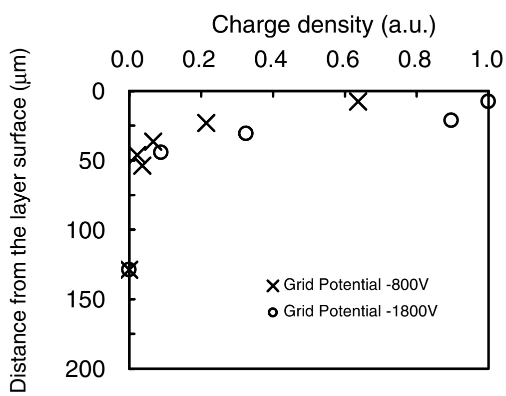


Figure 3. Charge density distribution within the particle layer on a conductive plate

Surface Potential and Charge Density Distribution of Particle Layers on an Insulative Film

As described in the previous section, under the charging condition where a pulsed current was observed, the charges exist only on the surface. However, to confirm the possibility of the existence of transients, we inserted an 11μm-thick insulative film between the conductive plate and the particle layer in Figure 1. The surface potential of the insulative film was measured after the particle layer was removed. We expect charge accumulation in the particle layer because the insulative film bock the flow of charge in to the conductive plate.

As shown in figure 4, the surface potential of the particle layer becomes the same as the grid potential. The surface potential of the insulative film rises at grid potential of –4000V or more and they are 0V and -900V at the grid potential of –4000V and -5500V, respectively. After the insulative film have charges on its surface, the potential difference of the particle layer itself dose not increase so much compared with the surface potential of particle layer.

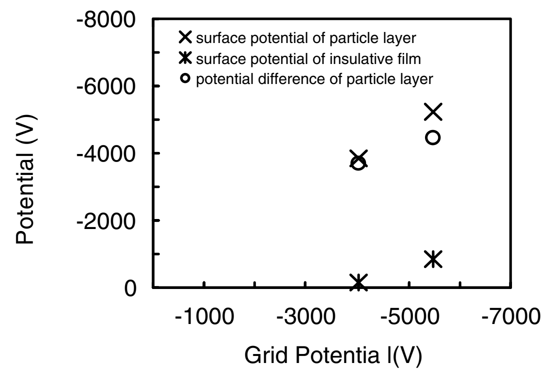


Figure 4. Relationship between the grid potential and each surface potential placed insulative film

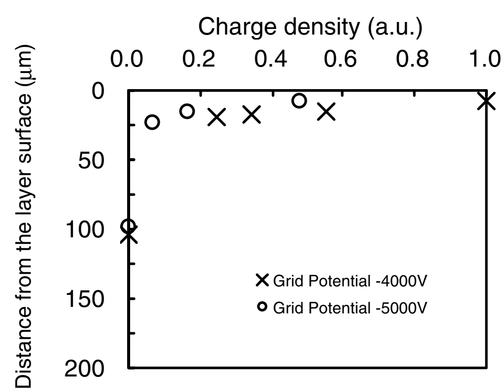


Figure 5. Charge density distribution within the particle layer on an insulative film

Figure 5 shows the charge quantity distributions within the particle layer when the gird potential is –4000V and –5000V. Note that the charges exist only in the surface layer of about 20μm-thick regardless of charge transfer to the insulative film surface.

Discussion

Validity of the Charge Density Distribution Measurement

In this chapter, we discuss the validity of the charge density distribution measurement.

When the charge density on a surface parallel to the support plate in the particle layer is assumed to be uniform and the charge density distribution in the depth direction within the particle layer is expressed as ρ(x), the potential within the particle layer is obtained by solving the Poisson equation (Eq.1) under the boundary conditions of Eqs. 2 and 3.

The surface potential of particle layer *Vs* is the value substituting layer thickness *d* for *x* in Eq.4. It is possible to represent V_s as Eq.6 via Eq.5. As explicitly expressed in the first coefficient of Eq.6, this term represents the center of gravity depth of the charges in the layer normalized with the thickness. Finally setting 1/*k* for the first coefficient of Eq.6, it expresses the relation among the surface potential V_s, the total charge quantity within the particle layer *Q*, and the substitution of charge distribution *k* as shown in Eq.7.

Consequently, we know the distribution condition of the charges within the particle layer by measuring *Vs* and *Q*, or we can obtain the charge quantity within the particle layer by measuring the surface potential if the charge distribution condition is known. Note that ε is $\varepsilon_0\ \varepsilon_r$, and ε_r is defined as $\varepsilon_r = \varepsilon_b p + (1-p)$ using the relative dielectric constant ε_b of the bulk material of the particles and the filling percentage *p* (typically about 50%) in the particle layer.[4] The *k* is called charge distribution coefficient in this paper.

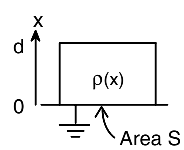
The charge distribution coefficients obtained from the experimental results shown in Fig. 3 were about 1.1. And the coefficients calculated by the surface potential and the total charge quantity in Eq. 7 at some various grid potentials were also 1.1~1.2. From these results, we infer that the charges exist surely only on the surface layer at any charge condition.

$$\frac{\partial\phi(x)}{\partial x^2} = -\frac{\rho(x)}{\varepsilon} \qquad (1)$$

(Boundary Condition)

$$\phi(0) = 0 \qquad (2)$$

$$\frac{\partial\phi(d)}{\partial x} = 0 \qquad (3)$$



$$\phi(x) = -\frac{1}{\varepsilon}\left\{\int\left[\int \rho(x)dxdx - x\int_0^d \rho(x)dx\right]\right\} \qquad (4)$$

$$V_s = \phi(d) = \frac{1}{\varepsilon}\int_0^d \rho(x)xdx \qquad (5)$$

$$= \frac{\int_0^d \rho(x)xdxS}{\int_0^d \rho(x)dxSd}\frac{d}{\varepsilon S}\int_0^d \rho(x)dxS \qquad (6)$$

$$= \frac{1}{k}\frac{1}{C}Q \qquad (7)$$

Discharge Model in the Particle Layer

In this section, we discuss the mechanism governing the charge density distribution in the particle layer.

As illustrated in Figure 6, the charges supplied from the charging device attach to the particles of the surface layer, and these attached charges form electric fields inside the layer without penetrating into the particle layer. If this electric field becomes larger than a certain threshold level, very small and discrete discharges would occur in the air-filled spaces within the particle layer. These discharges occur sporadically at any sites within the particle layer, and the generated positive and negative charges are recombined or adhere to particles. When negative charges are generated in boundary parts between the particle layer and the conductive plate, they flow into the conductive plate or settle onto the film in case that insulative film is placed. A particle layer can be equivalently treated as one polarized layer. A charge quantity of the particles in the middle layer was not observed because the positive and negative electric charges are of similar quantities even if they attached to the particles. This is why charges are only observed near the surface of the particle layer even when the charging quantity saturates and these discharges prevent from increasing the potential of the particle layer (i.e., the charge quantity). The movement of the charges generated by the discharges can be observed as an electric current through the conductive plate.

Consequently, we think that the maximum charging quantity of the particle layer is determined by the electric fields to initiate discharge in the particle layer, and it is equivalent to the surface potential of the particle layer.

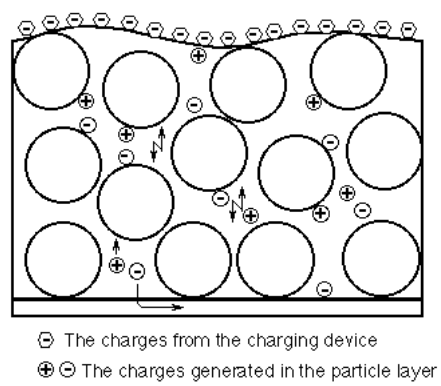


Figure 6. Schematic illustration of discharge image within a particle layer

Verification Experiment

We carried out the following experiments to verify the above-described model.

We fixed the particle layer directly below the charging device and observed the current with gradual change of the grid voltage under 1atm and 0.76atm in the experimental apparatus shown in Fig. 1. The grid voltages considered to initiate the discharges were –3kV for the former case and –2kV for the latter case. In a separately-done experiment, the discharge initiating voltage of the charging device itself were –4.1kV and –2.9 kV respectively. We believe that discharges occur in the air-filled spaces within the particle layer because the decrease ratio of the discharge initiating voltage for both cases are roughly the same level.

Charging Rate

Theoretical Equation

The charging rate of an insulative layer with a corona charging device having a grid electrode can be expressed by Eq.8 on the following assumption. The charge density N_0 in a charging field is proportional to the difference between the grid potential and the surface potential of the insulative layer. The electric field in a charging field is uniform and the distance between the grid and the insulative layer surface is large enough compared with the insulative layer thickness. The charge quantity as a function of time (Eq.9) is obtained by solving Eq.8 putting q(0) = 0 as an initial condition. In this expression, so-called time constant is defined as Q_{inf}/i_0.

$$\frac{dq(t)}{dt} = N_0 \frac{V_g - q(t)/C}{V_g} e\mu \frac{V_g - q(t)/C}{l} S \tag{8}$$

$$\begin{aligned} q(t) &= \frac{N_0 e\mu CSV_g t}{Cl + N_0 e\mu St} \\ &= Q_{\text{inf}} \frac{t}{Q_{\text{inf}}/i_0 + t} \qquad \left(\because N_0 e\mu = \frac{i_0/S}{V_g/l} \right) \\ &\quad wherein \quad Q_{\text{inf}} = CV_g \end{aligned} \tag{9}$$

N_0: space charge number density at q =0
e : elementary charge
m : mobility of charge
i_0 : arriving current at insulative layer at q = 0
V_g: grid potential
l : distance between grid and insulative layer surface
C : capacitance of insulative layer
S : charging area

Experiment

We measured the transition of the surface potential of an insulative film by changing the stage moving speed of the apparatus in Fig. 1. In this experiment, no particle layers ware formed on the insulative film for precise experiments. Also we changed the arriving current at insulative layer surface i_0 of when q = 0 independently by adjusting the discharge wire current of the corona charging device. We used the current value into the grounded conductor surface without the insulative layer as i_0. Figure 7 shows calculation results and measurement results setting Vg = -1000V.

The calculation values become somewhat lower, but this is caused by the ununiform electric fields. Because the electric fields determined by the wire potential affect the charging field beyond the grid, some errors occur in the charge density and charge velocity. In place of obtaining the correct electric field distribution, we can know the actual transition with good precision as follows. We obtain the grid potential V_0 when i_0 = 0A, and substitute V_g-V_0 for V_g in the above equation. The darkest line in Fig. 7 shows the corrected calculation results using the results of measured V_0 = +20V and it well agrees with the actual results.

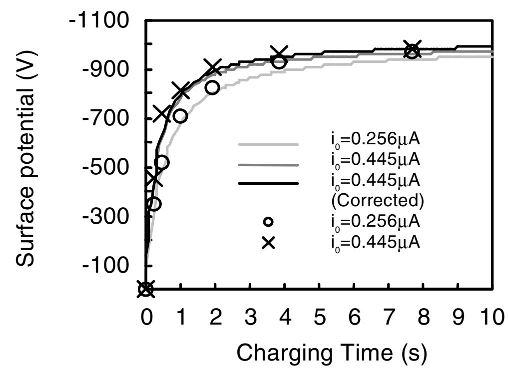


Figure 7. Transition of the surface potential

To summarize this discussion, a charge quantity of particle layer formed with insulative fine particles of micron-order is defined by three elements. One is the charge distribution coefficient and another is the charging quantity relaxation by discharges within the particle layer, and the other is relation expressed in Eq.9. Eq.10 is the expression including these three elements.

$$\begin{aligned} Q &= kCV_g \frac{t}{kCV_g/i_0 + t} \\ wherein \quad Q &\le k\varepsilon SE_{st} \\ k &= 1.1 \sim 1.2, \quad E_{st} \cong 7 \times 10^6\, V/m \end{aligned} \tag{10}$$

Conclusions

When the charge quantity is increased, the surface potential becomes the maximum charge quantity. And the charge quantity equivalent to this surface potential can be maintained in the particle layer.

We proposed a discharge model in a particle layer to determine the maximum charge quantity. This model has proved valid by our experiment.

We derived the theoretical equation of the charging rate and it well fit to the experimental values.

We formulated the charge quantity of a particle layer including its time dependance.

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Biography

Furukawa Kazuhiko received B.S. degree from Osaka University in communication engineering in 1990. He belongs to the Production Technology Development Center and has worked mainly on charging process as well as electrophotographic process since he joined the SHARP Corporation in 1990. His current research interests include plasma technique. He is a member of the Imaging Society of Japan and The Institute of Electrostatics Japan.