# A Study of Non-Uniform Charging by Charging Roller with DC Voltage

**M. Kadonaga, T. Katoh and T. Takahashi**

*Research and Development Center, Ricoh Company, Ltd., Yokohama, Japan*

Model experiment and numerical simulation are carried out in order to make clear the generating mechanism of non-uniform charging by charging roller with DC voltage. From the experiments using metal roller and polyethylene terephthalete (PET) sheet, the periodic charging patterns can be recognized on the PET sheet by cascade development with toners after the sheet is charged. The period and the size of the patterns become large as the applied voltage increases. The shapes of the patterns are different between positive and negative charging. The characteristic of the patterns is similar to that of separating discharges on an electrified insulating sheet. The results show that the charging patterns are made as follows. (1) Abnormal discharge occurs between the charging roller and the PET sheet, and large amount of charge is deposited on the sheet. (2) The charge is forced to move due to surface discharge. On the other hand, two-dimensional electrostatic simulation of the charging roller is carried out with consideration of the surface discharge as well as the abnormal discharge. From the simulation, the periodic charging patterns can be generated on the PET sheet and may verify the new model of generating non-uniform charging patterns as proposed above.

Journal of Imaging Science and Technology 43: 274–279 (1999)

## Introduction

A charging roller system is one of the contact charging devices of electrophotographic machines. Recently it has become popular because of extremely less ozone emission than corona charging devices.[1] Figure 1 shows a schematic diagram of the charging roller system with DC voltage. The system consists of the photoconductor (OPC), the charging roller and the DC power supply. The electric discharge happens between the roller and the OPC, and thus the surface of the OPC is charged. It is difficult to obtain uniform charging by roller with DC voltage and the periodic charging patterns can often be observed on the OPC, especially by a single-layer roller with low resistance. Because the periodic charging patterns degrade the quality of printing image, they must be eliminated and uniform charging is desired.

In order to obtain the uniform charging, AC voltage is often superimposed on DC voltage. However, with DC+AC voltage, a great deal of discharge happens in the vicinity of the nip between the OPC and the roller. Ozone is generated by discharge and it degrades the OPC which is very sensitive to the ozone.

When various kinds of proper material are used for the elastic layer and the surface layer of the charging roller, non-uniform charging can be suppressed even though with only DC voltage the OPC degradation rarely happens due to less ozone emission. However, the generating mechanism of such non-uniform charging patterns on the OPC is not still clear. In order to make clear the generating mechanism of non-uniform charging by charging roller with DC voltage, model experiment and numerical simulation are carried out.

## Objective

The objective is to make clear the generating mechanism of the non-uniform charging patterns by a charging roller with DC voltage.

## Experiments

**Experimental Setup.** Experimental setup model of the charging roller is constructed as shown in Fig. 2. The metal roller is used due to its extremely low resistance, so as to obtain large and clear periodic charging patterns. PET (polyethylene terephthalete) sheet with 25 micron thickness, back coated with aluminum, is used instead of OPC because of its similar electrostatic char-

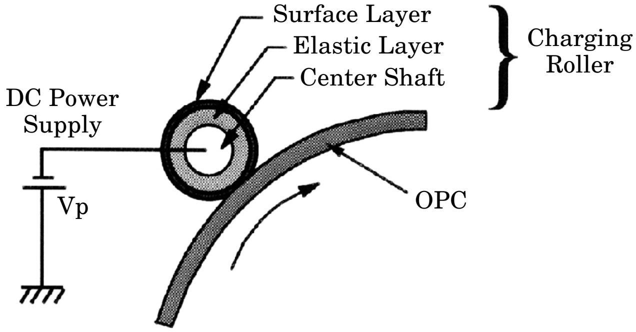


**Figure 1.** Schematic diagram of the charging roller system with DC voltage.

Original manuscript received June 9, 1998

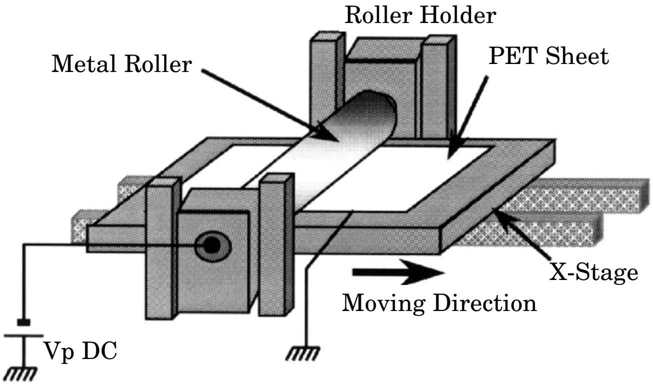


**Figure 2.** Schematic diagram of the experimental setup.

acteristic. The PET sheet is set on the $x$-stage and moves at the speed $V_L$ under the roller biased with DC voltage. The roller is rotated simultaneously as the PET sheet moves due to the surface friction. After the PET sheet is charged, the non-uniform charging patterns can be observed by cascade development with toners. When negative voltage is biased on the roller, positive toners are used to develop, and vice-versa.

On the other hand, the surface potential distribution, before development with toner, is measured by two methods. The first method is by the conventional electrostatic surface potential meter (TREK MODEL 344, Medinam, New York, USA), whose resolution is more than 1 mm. The second method is the high resolution electrostatic surface potential meter using a scanning electrostatic force microscope,[2] whose resolution is about 30 μm.

**Experimental Results.** A series of non-uniform charging patterns for various negative DC voltages is shown in Fig. 3. The PET sheet moves upwards at the speed of 2.4mm/s as the arrow shows in Fig. 3(a). The diameter of the roller (D) is 12mm. The generating pattern looks like a stripe or a round shape. The size (width) and the period of the pattern in the moving direction becomes large as the applied voltage (Vp) increases. Along the length of the roller, non-uniformity also exists. When *Vp* is small, discharge may happen simultaneously along the length of the roller and the patterns are stripes. On the other hand, when *Vp* is large, discharge may happen one by one, and the patterns become isolated and are deposited in interleaving parallel rows. As the applied voltage increases, the discharge gap becomes longer and the discharge may become more unstable.

The experiments are also carried out under the condition that $V_L$ = 40 mm/s and $D$ = 40 mm, and the results resemble those shown in Fig. 3. As the roller is a conductor and the PET sheet is an insulator, discharge phenomenon in this experiment may be independent of $V_L$ and $D$. The discharge gap is not effected much even though the roller diameter is changed when the applied voltage is the same. The results shown in this paper are all carried out under the condition that $V_L$ = 2.4 mm/s and $D$ = 12 mm.

By the conventional electrostatic surface potential meter, TREK MODEL344, such non-uniform charging potential distribution is not able to be measured. If the conventional meter is used, only average potential value is obtained because of its course resolution. Figure 4 shows the relationship between the applied voltage and the average surface potential obtained by the TREK MODEL344. The straight line in Fig. 4 shows the ideal charging characteristic deduced from Eq. 1.[3] The experimental results are deviated from the ideal charging characteristic.

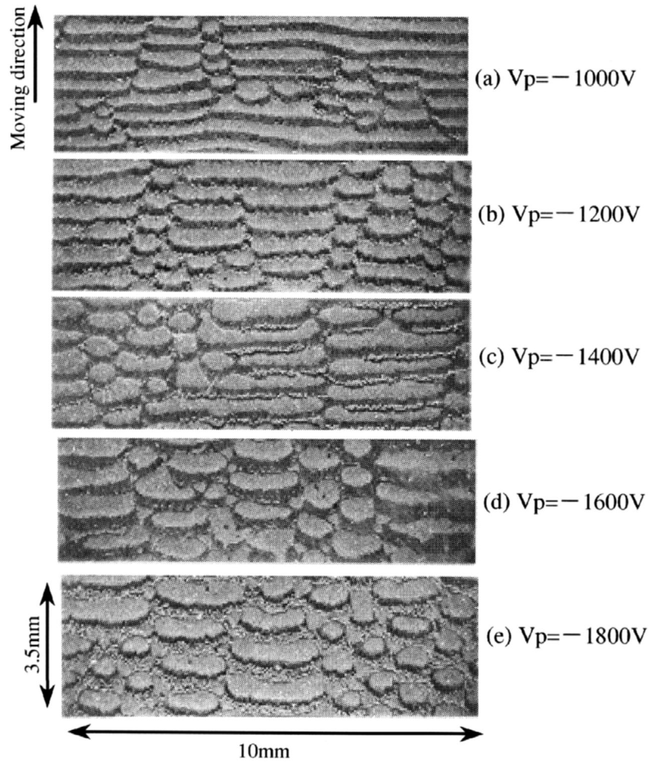


**Figure 3.** The series of the non-uniform charging patterns for various negative DC voltages.

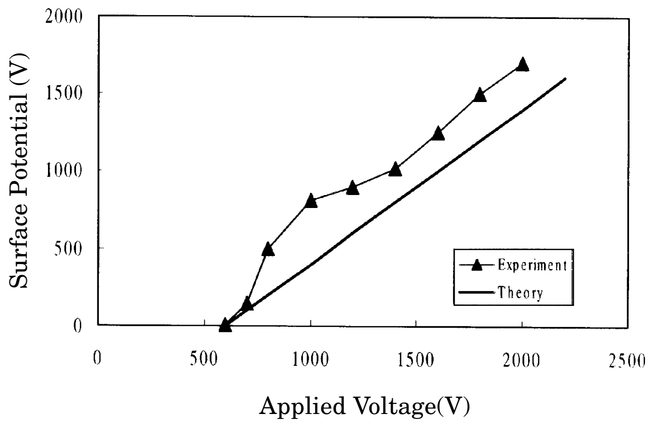


**Figure 4.** The relationship between the applied voltage and average potential value of the PET sheet with negative charging.

$$Vs = Vp - 312 - 6.2(d/\varepsilon') - (7737.6d/\varepsilon')^{1/2} \quad (1)$$

where
- $d$: Thickness of the PET sheet [m]
- $\varepsilon'$: Relative dielectric constant of PET
- $Vp$: The applied voltage [V]
- $Vs$: The ideal surface potential value [V]

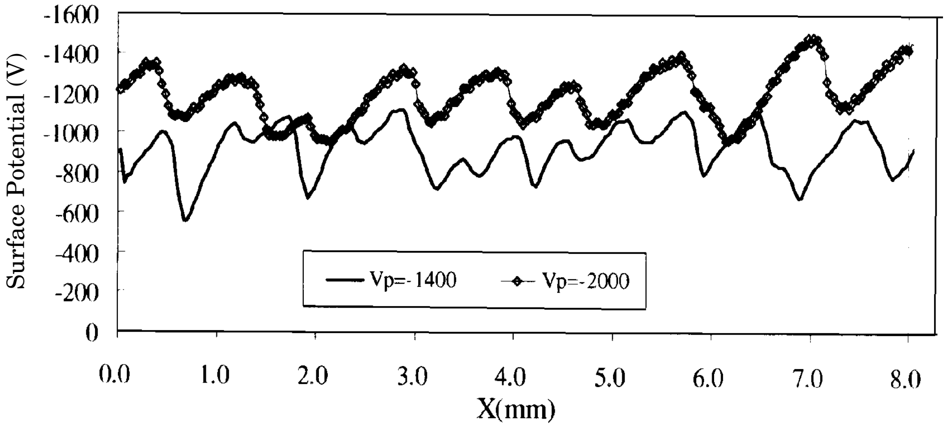


**Figure 5.** The potential distribution of the PET sheet along the moving direction in the case of negative charging.

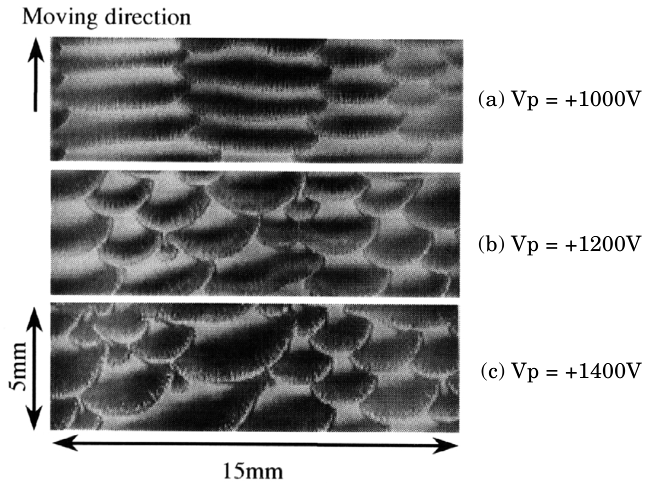


**Figure 6.** The series of the non-uniform charging patterns for various positive DC voltages.

Figure 5 shows the potential distribution along the moving direction measured by the high resolution electrostatic surface potential meter. The surface potential is measured at intervals of 32 μm and it is enough to show the non-uniform charging distribution corresponding to Fig. 3. It is recognized from Figs. 3, 4 and 5 that unstable discharge may happen in the gap between the roller and the PET sheet.

Figure 6 shows a series of the non-uniform charging patterns for various positive DC voltages. The pattern looks like a tree-like shape with fine notches at the lower edge of each pattern and is completely different from that of negative charging. However, the characteristic of the patterns are similar to that of separating discharge patterns[4] and the Lichtenberg's figures.[5] Compared with these discharges, charge on the PET sheet may be forced to move because of surface discharge.

From these experimental results, two effects should be considered in modeling the generating mechanism of non-uniform charging patterns. The first effect should be the abnormal discharge between the roller and PET sheet. The second effect should be the surface discharge on the PET sheet.

## Non-Uniform Charging Model

A new model for generating the non-uniform charging patterns along the moving direction is proposed. As the non-uniformity exists in two-dimensional, three-dimensional consideration is desired. Such non-uniformity in both directions may be due to abnormal discharge. If non-uniformity in the moving direction can be eliminated, non-uniformity along the length of the roller will disappear simultaneously. Therefore, this article focuses on the non-uniform charging along the moving direction. Figure 7 shows the time sequence of this model near the entrance of the nip between the roller and the PET sheet. First, strong discharge occurs in the large gap between the roller and the PET sheet. Large amounts of charge are deposited on the PET sheet by abnormal discharge [Fig. 7(a)]. The potential of the PET sheet, where the charge is deposited, is so high that the surface discharge takes place [Fig. 7(b)]. Because the potential of the discharge point on the PET sheet remains high, following discharge cannot take place for a while [Fig. 7(c)]. As the sheet moves and the highly charged part is far enough from the discharge point, the potential of the sheet at the same position decreases and then discharge occurs again [Fig. 7(d)].[6] The same steps repeat successively, and finally non-uniform charging patterns can be generated on the PET sheet.

## Numerical Simulation

**Simulation Model.** Even though numerical simulations of one-dimensional analysis for the charging roller are very popular,[3,7,8] they cannot simulate this new model of generating non-uniform charging patterns. In order to certify this new model, two-dimensional simulation of the charging roller is carried out according to the following four steps.

**Step 1:** ***Calculation of the electrical field*** to obtain the potential distribution around the roller and the PET sheet. Boundary fitting coordinate mesh is used to fit the roller shape. Poisson's equation is solved by the finite difference method considering the movement of the PET sheet.

**Step 2:** ***Consideration of the discharge*** between the roller and the PET sheet. Using Paschen's law for the breakdown voltage ($V_{pa} = 312 + 6.2 \times 10^6 \bullet g$), the discharge gap can be derived. In the case of normal discharge, when the discharge occurs at the gap $g[m]$, the amount of charge ($dQ$)

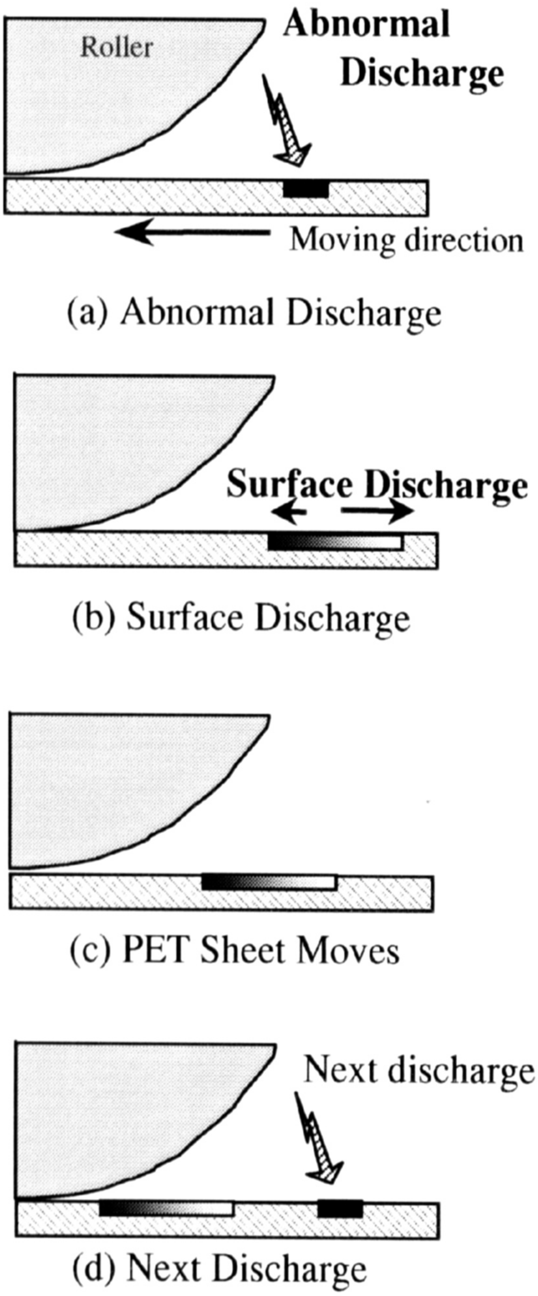


**Figure 7.** Model of generating non-uniform charging patterns.

deposited on the sheet is estimated from Eqs. 2 and 3.[9] Equation 3 indicates that the discharge occurs when the voltage across the gap ($Vg$) is slightly larger than $V_{pa}$ and stops when $Vg$ becomes equal to $V_{pa}$.

$$dQ = (d + \varepsilon' \cdot g) \cdot \varepsilon_0 \cdot \Delta V/(d \cdot g) \qquad (2)$$

$$\Delta V = Vg - (312 + 6.2 \times 10^6 \cdot g) \qquad (3)$$

On the other hand, in the case of abnormal discharge, Eq. 4 may be used instead of Eq. 3. This equation and the value of β are determined so as to fit the experimental results shown in Fig. 8 explained later. Equation 4 indicates that abnormal discharge occurs when $Vg$ is slightly larger than $V_{pa}$ and it cannot stop when $Vg$ becomes equal to $V_{pa}$. The voltage drop of $Vg$ becomes larger than that of normal discharge because of large amount of $dQ$. This equation is only empirical, but the large value of $dQ$ is deduced from Eqs. 2 and 4 when the discharge gap $g$ is large.

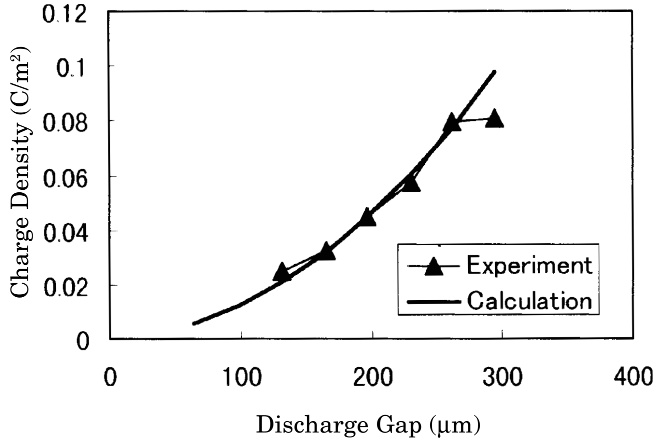


**Figure 8.** The relationship between the discharge gap and discharge density in negative charging.

$$\Delta V = Vg - \beta \cdot g^2 \qquad (4)$$

where

- $d$: Thickness of the PET sheet [m]
- $g$: Discharge gap [m]
- $\varepsilon'$: Relative dielectric constant of PET
- $\varepsilon_0$: Dielectric constant of air
- $\beta$: The parameter for the abnormal discharge
- $Vg$: Voltage across the discharge gap
- $\Delta V$: Voltage drop of $Vg$ due to the discharge

Figure 8 shows the relationship between the discharge gap $g$ and discharge density by one abnormal discharge. The values of triangles are estimated from Fig. 4 with the assumption that the charge would be deposited in one mesh by one abnormal discharge. The solid line in Fig. 8 shows the relationship obtained with Eqs. 2 and 4 when the parameter for the abnormal discharge β is $1 \times 10^{12}$. The value of β may depend mainly on the material and the resistance of the roller.

**Step 3:** ***Consideration of the surface discharge.*** The electrical field after the abnormal discharge is recalculated because the abnormal discharge disturbs the electrical field. Next, the electrical field strength $E$ is estimated at every point on the sheet. If the value of the electrical field strength is larger than the $E_{limit}$, which is the breakdown field strength of the surface discharge, surface discharge may happen and charge ($dq$) is forced to move in the direction according to the electrical field around the point.

$$dq/dt = \alpha \cdot E \text{ (in case of } E > E_{limit}) \qquad (5)$$

In this study, $E_{limit} = 3.5 \times 10^6$[V/m] and $\alpha = 4 \times 10^{-7}$ are used. The value of $E_{limit}$ is determined in order to simulate the pitch of the patterns as close as possible to the

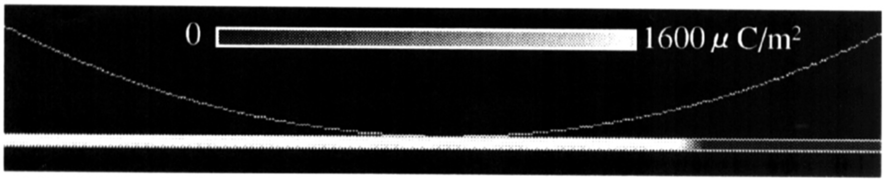


**Figure 9.** Uniform charging ($Vp$ = 1600 V).

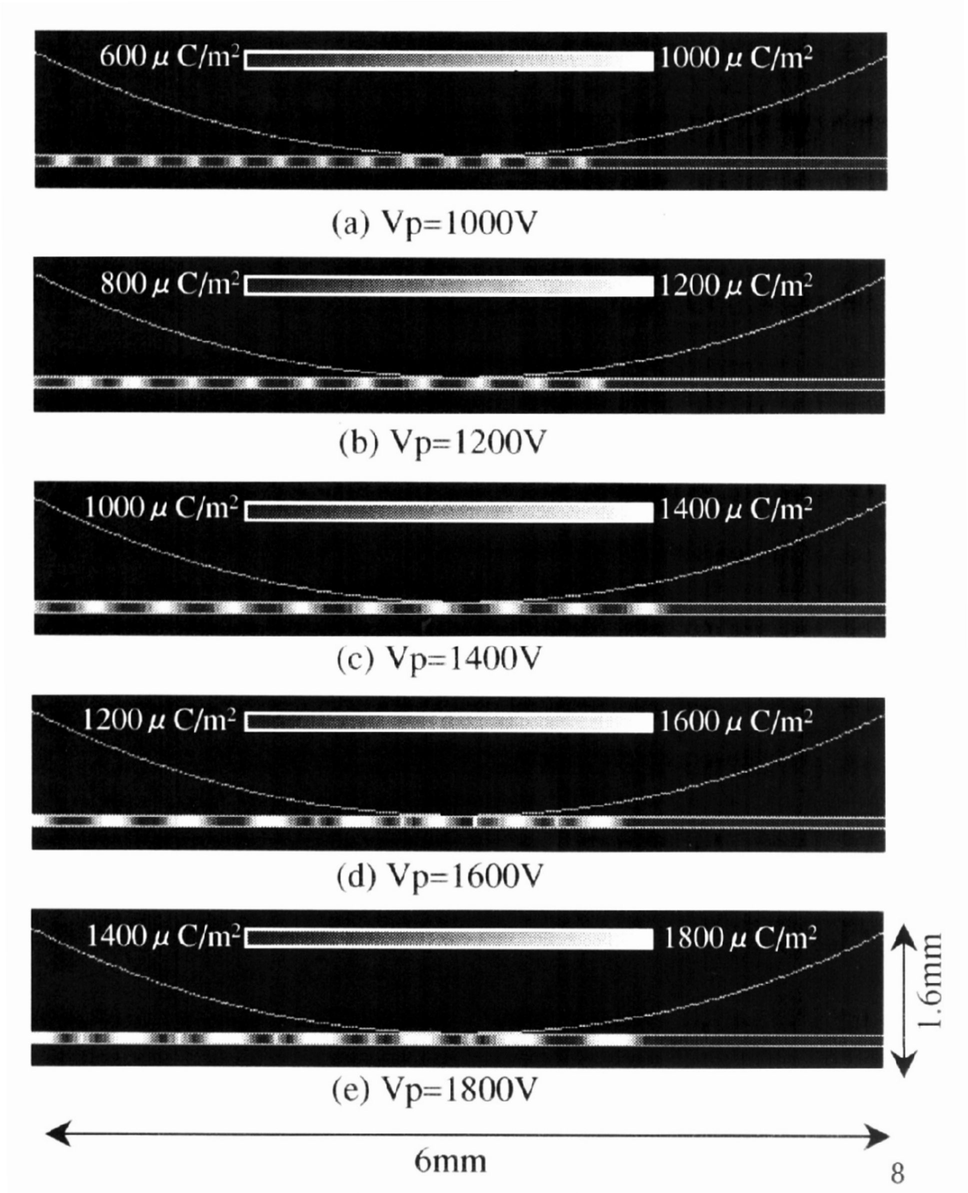


**Figure 10.** Non-uniform charging.

experimental result. The parameter α acts something like a resistivity against the surface discharge current. The value of α has no effect on the final discharge pattern if it is sufficiently small, because Step 3 should be repeated until surface discharge does not occur at any point on the PET sheet. After Step 3, the electrical field at time $T$ is obtained.

**Step 4: Time is advanced** ($T = T + dt$). The PET sheet moves forwards, then back to Step 1 and repeats the same steps successively.

## Simulation Results

Numerical results are shown in Figs. 9 and 10 that indicate the charge distribution on the PET sheet in gray scale. Figure 9 shows the uniform charging if the abnormal discharge does not occur (using Eqs. 2 and 3). This is the ideal charging by the charging roller. Figure 10 shows the non-uniform charging patterns when the abnormal discharge and the surface discharge take place (using Eqs. 2, 4 and 5). The bright portions indicate highly charged places. (a) is the case of $Vp$ = 1000 V, (b) $Vp$ = 1200 V, (c) $Vp$ = 1400 V (d) $Vp$ = 1600 V and (e) $Vp$ =

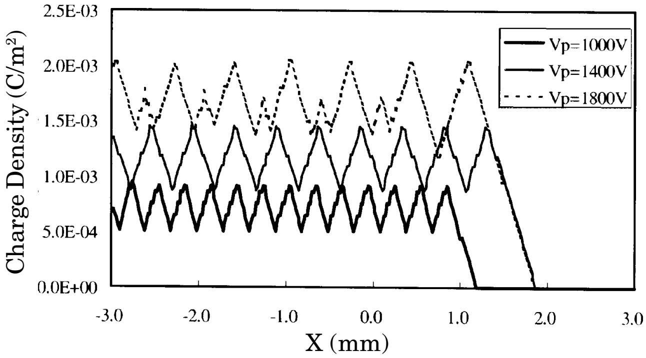


**Figure 11.** The charge distribution on the PET sheet obtained by calculation.

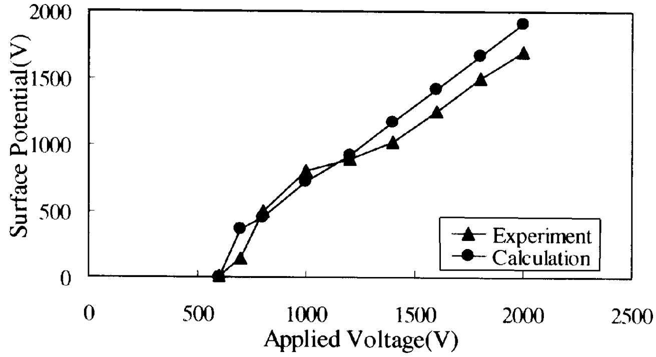


**Figure 12.** The comparison of the charging characteristic result between experiment (negative charging) and calculation.

1800 V. Non-uniform periodic charging patterns can be recognized on the PET sheet. Figure 11 shows the charge distribution on the PET sheet for various applied voltages. Figure 12 shows the comparison of the charging characteristic result between experiment and calculation. The calculation result shows good agreement with the experimental result. The comparison of the period of the patterns between the experiment from Fig. 3 and calculation from Fig. 10 is shown in Fig. 13. The period of calculation shows smaller value than that of experiment. This discrepancy is probably due to the difference of the positioning of the patterns between 2-D and 1-D. In Fig. 3, patterns are deposited in interleaving parallel rows and the period may become larger than that in one-dimensional even parallel rows. Even though there is discrepancy between experiment and calculation, size and period of the charging patterns become large as applied voltage is increased. This calculation result may certify the new model of generating non-uniform charging patterns proposed in this article.

## Conclusion

The experiment to clarify the mechanism of the non-uniform charging by charging roller with DC voltage is carried out together with the numerical simulation. The abnormal discharge and the surface discharge on the OPC may cause the non-uniform charging patterns. Considering the abnormal discharge and the surface discharge, the relationship between the pattern and the applied voltage is simulated numerically and shows good agreement with the experimental result.

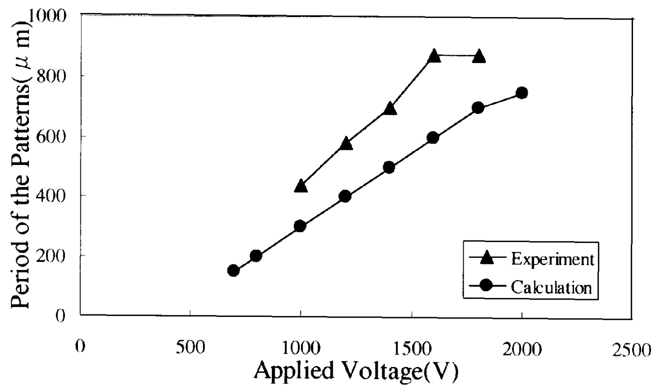


**Figure 13.** The comparison of the period of the patterns between experiment (negative charging) and calculation.

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