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Ozone Generation in Corona Discharge at Pin Electrode of Electrophotography Charger

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Abstract

The generation of ozone in a stable regime of DC corona discharge at a pin electrode is modeled to provide data that can be utilized for the evaluation of charging and transferring devices of electrophotography with respect to reducing the ozone emission. The results of a theoretical investigation show the following: (1) The ozone generation rates of the 50 μm radius pin electrode are 0.085 ppm/μA and 0.010 ppm/μA under 5 liter/min air flow rate in case of negative corona and positive corona, respectively. The generation rate increases in accordance with the increase of the pin radius. Although the rate of ozone emission is nonlinear with respect to the discharge current, it can be assumed to be approximately linear within the usual design and operation conditions of electrophotography chargers. In case of the positive corona, ozone is formed just at the surface of the discharge electrode, but on the contrary, in case of the negative corona, ozone is formed at about 0.1 mm apart from the tip of the electrode. (2) The ozone generation rate of the charger with saw-tooth electrodes is reduced to about one third of that with a biased charger roller and it is only 1/140 of that with a corotron. The saw-tooth charger has a potential to realize virtually ozone-free charger.

Introduction

One of the most important issues of electrophotography technology is to reduce ozone emitted by charging and transferring devices, such as corotrons, scorotrons[1] or biased contact rollers[2-5], because not only does ozone damage photoreceptors and consequently causes the deterioration of images, but it is also harmful for humans.[6] For this reason, several experimental and theoretical works have been performed on ozone synthesis in the gas discharge field. Nashimoto[7] carried out a parametric experiment on corotrons to investigate the effects of discharge wire and shield materials, wire diameter, and the difference of positive and negative corona. Naidis[8] established an elegant theoretical model that can be used to predict the rate of plasma chemical processes in stable positive and negative corona discharges between the wire and a coaxial cylinder. The author[9] modified Naidis' model to carry out more accurate calculation on ozone emission from the corotron. However, because ozone emission from the corotron is still substantially high, the biased contact charger roller has been developed for a new charging device to realize extremely low ozone emission.[2-5, 10] The system consists of a highly electroresistive elastmer roller and a power supply. DC voltage superposed on AC voltage is applied between the photoreceptor drum and the charger roller. The electrical micro-discharge in the vicinity of the nip controls the charging of the photoreceptor.[10] Although ozone is also formed in this system due to the electrical discharge, it is extremely small.[11] An ozone filter is usually not necessary to satisfy an environmental standard using this charger. Hence it is sometimes termed the virtually ozone free charger. However, the contact charger roller is used only in the low-speed machine, for the photoreceptor rapidly wears in this system due to the mechanical contact between the charger roller and the photoreceptor. Alternative discharge current induced by the application of AC voltage accelerates the wear of the photoreceptor, because active ions generated in the vicinity of the contact area attack the organic photoconductor. It is believed that the wear mechanism is similar with the ion etching. Furthermore, it is difficult to realize uniform charging using this charger for high-speed machines.[10]

Another new ozone-free charger was proposed by Furukawa et al.[12, 13] It has saw-tooth electrodes to which DC high voltage is applied through each resistor as schematically shown in Figure 1. It was confirmed that interposed resistors control sway and dispersion of discharge current from each discharge electrode. Consequently it can uniformly charge the photoreceptor with less discharge current and an amount of generated ozone is less than that of the former charging device[14] with parallel-connected saw-tooth electrodes to which high voltage is directly applied. In this study, the author has established a theoretical model to calculate ozone emission from this new device that has a potential to realize the ozone-free charger applicable for high-speed machines. The results of the calculation were compared with experimental results and some fundamental characteristics and feasibility for the electrophotography charger have been discussed.

Modeling

Ozone Generation Rate in Corona Discharge

One of saw-tooth electrodes is assumed to be a pin-to-plate system shown in Figure 2(a). It is further simplified to the one-dimensional concentric sphere-to-sphere geometry shown in Figure 2(b). High voltage, larger than a corona ignition voltage, is applied between the inner and the outer sphere. The plasma reaction rate W, number of ozone molecules generated per unit time, is

$$W_{\pm} = \frac{I}{e}\int_{r_0}^{R}\psi_{\pm}(r)\alpha_r(r)dr\,. \qquad (1)$$

Here, I is a total discharge current, e is the charge of the electron, R is the radius of the outer sphere (collecting electrode), and r_0 is the radius of the inner sphere (discharge electrode). Subscripts + and − mean positive and negative corona, respectively. Two parameters, the ratio of the electron current and the total current ψ and the reaction rate constant α_r, are analytically expressed based on Townsend theory as a function of the electric field $E(r)$.[8, 9, 11]

$$\alpha_r(r) = An_m \exp\left(-\frac{Bn_m}{E(r)}\right),$$

$$\psi_+(r) = \exp\left(\int_{r_0}^{r} -\alpha_+(r)dr\right),\ \alpha_+(r) = Cn_m \exp\left(-\frac{Dn_m}{E(r)}\right)$$

$$\psi_-(r) = \gamma\exp\left(\int_{r_0}^{r} -\alpha_-(r)dr\right),\ \alpha_-(r) = Cn_m \exp\left(-\frac{Dn_m}{E(r)}\right) - Fn_m\,,$$

where α and γ are the first and the second Townsend ionization coefficients, $\ln(1/\gamma) = 8$, n_m is the concentration of molecular oxygen, and A, B, C, D, and F are experimental constants, $A = 5.6\times10^{-20}$ m^2, $B = 2.1\times10^{-19}$ Vm^2, $C = 3\times10^{-20}$ m^2, $D = 8\times10^{-19}$ Vm^2, $F = 2\times10^{-23}$ m^2.[8, 14, 15] Equation (1) can be numerically integrated using the Simpson's integral method and the ozone concentration c (ppm) is calculated at a certain air flow rate Q (liter/min), $c = 2.23\times10^{-15}\,W/Q$.

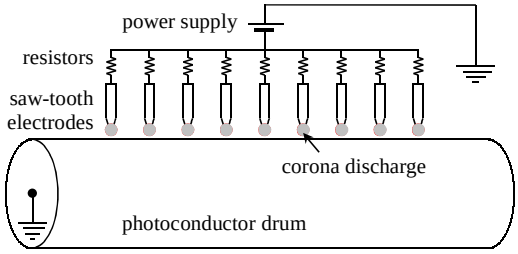

Figure 1. Schematic drawing of new charger with parallel-connected saw-tooth electrodes to which high voltage is applied through each resistor.

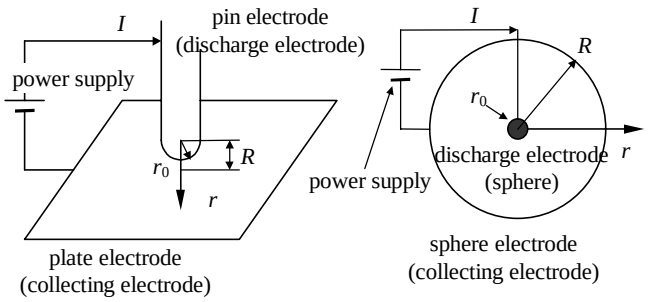

Figure 2. Configurations of (a) pin-to-plate electrode and (b) sphere-to-sphere electrode model.

Distribution of Electric Field

If the discharge current is small and thus there are negligibly small ions and/or electrons in the field, distribution of the electric field is derived from the Laplace equation.[16] That is, $E = E_0(r_0/r)^2$, where $E_0 = E(r = r_0) = V/r_0$. However, because the electric field of corona discharge is determined not only by the electrostatic potential ϕ, but also by the ionic charge density ρ, the distribution of the electric field deviates from the Laplacian form. The electric field in the discharge field is determined by the conservation low of charge $\nabla\cdot(-\omega\rho\nabla\phi) = 0$ and Poisson's equation $\nabla^2\phi = -\rho/\varepsilon_0$ (ω is the mobility of ions and ε_0 is the permittivity of free space), if diffusion and convection of charged particles are neglected and the field is assumed to be unipolar.[16] These two coupled differential equations can be analytically solved in the one-dimensional spherical coordinate under the boundary condition, $E = E_0$ at $r = r_0$.

$$E(r) = E_0\left(\frac{r_0}{r}\right)^2\sqrt{1+\frac{I}{6\pi\varepsilon_0\omega r_0E_0^2}\left\{\left(\frac{r}{r_0}\right)^3-1\right\}}\,. \qquad (2)$$

Equation (2) coincides with the Laplacian form in case of no discharge ($I = 0$) but the distribution of the electric field is relaxed under discharge condition.

Because it was experimentally confirmed that the electric field at the surface of the discharge electrode preserves the value determined by the corona ignition voltage,[17] the electric field at the surface of the discharge wire E_0 is calculated by the Naidis' method*1 or Peek's formula.*2 Result of numerical calculation shown in Figure 3 indicates that calculated results by two methods coincide fairly well with each other. Naidis' method is used in this report.

*1 The electric field at the surface of the discharge electrode is implicitly determined by the following integral equation.[8]

$$\int_{r_0}^{R} Cn_m \exp\left(-\frac{Dn_m}{E_0r_0^2}r^2\right)dr = \ln\left(\frac{1}{\gamma_{ph}}\right),$$

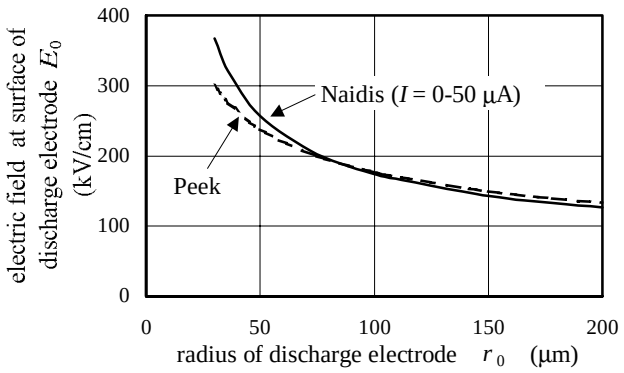

Figure 3. Radius of discharge electrode vs. electric field at the surface of discharge electrode (R = 20 mm).

where γ_{ph} is the effective photoionization coefficient [$\ln(1/\gamma_{ph}) = 8$]. Simpson's method was used for numerical integration and simple bisection method was applied to derive E_0 implicitly. It was numerically deduced that E_0 is almost independent of R and I at the usual geometry $R/r_0 > 3$ and the actual operating condition $I < 50$ μA.

*2 Peek's formula was experimentally determined from spark ignition voltages in sphere-to-plate systems.[14]

$$E_0 = 27.9\delta\left(1+\frac{0.533}{\sqrt{\delta r_0}}\right) \text{ (kV/cm, } r_0\text{: cm)},$$

where δ is a relative air density, $\delta = 0.386p/(273+T)$, p: pressure (mmHg), T: temperature (°C).

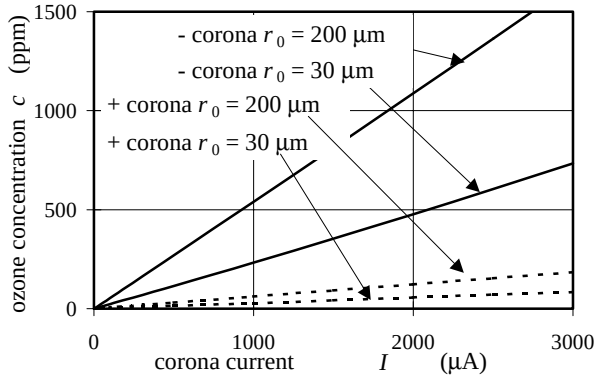

Figure 4. Linearity of ozone generation with respect to corona current (calculated, Q = 1.5 liter/min, R = 20 mm).

Effect of Discharge Current

Figure 4 shows the relationship between the discharge current and the calculated ozone concentration. Since the electric field depends on the discharge current, the calculated ozone concentration is not exactly proportional to the discharge current. However, the nonlinearity is negligibly small under actual operating conditions. This characteristic is same as that of the corotron[7, 9] and was experimentally confirmed in the pin-to-plate system as reported in the references 13, 18, and 19.

Distribution of Electron Current and Ozone Formation Rate

Figure 5 and 6 show the calculated distributions of the electron current ratio $\psi_{+/-}(r)$ and the differential ozone formation rate $\psi_{+/-}(r)\alpha_r(r)$, respectively, in positive and negative corona. It is clearly recognized that in the case of the positive corona the electron current is high at the surface of the discharge electrode and ozone is formed just at the surface, because electrons migrate toward the tip of the discharge electrode and are concentrated at the tip. On the contrary, in the case of the negative corona ozone is formed about 0.1 mm away from the discharge electrode. The balance between the electron divergence from the negative discharge electrode and the decrease of the electric field determines the peak of the ozone formation rate at about 0.1 mm away from the discharge electrode. These characteristics were also same as those of the corotron[9] and supported by the experimental results that the thickness of luminescence in negative discharging was about 0.1 mm[20] and it was larger than that in positive discharging.[19]

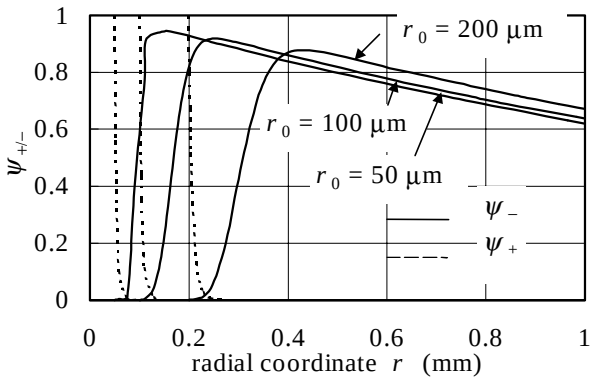

Figure 5. Distribution of the ratio of the electron current and the total current.

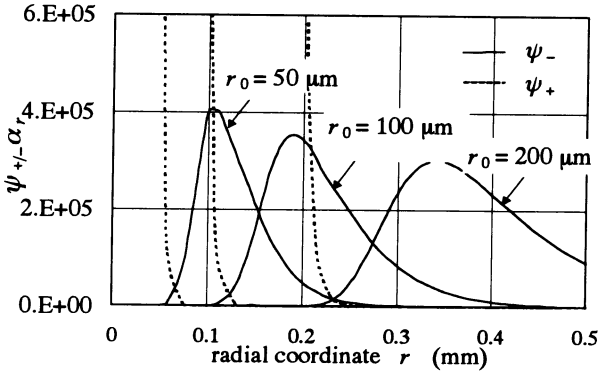

Figure 6. Distribution of ozone generation rate.

Ozone Generation Rate

Figure 7 shows the relationship between the radius of the discharge electrode and the ozone generation rate. The experimental data in this figure were adopted from references 13, 18, and 19. Since the ozone generation rate is assumed to be almost linear with respect to the discharge current, averaged rates of experimental data were plotted in Figure 7. Furthermore experimental values were normalized at the conditions of 20 °C temperature, zero humidity, and 3 m/s air flow velocity using experimental data on the influences of these factors.[18, 21] The results of the investigation show the following:

(1) The calculated rate of the ozone emission by the negative discharge agreed fairly well with experiments. However, a substantial difference existed in the positive discharge. This characteristic is just similar with that of the corotron and the reason seems to be also common with the case of the corotron.[9] That is, this discrepancy is probably due to catalytic properties of electrode materials. According to Nashimoto's report,[7] the ozone formation is affected by materials used for the discharge electrode, in particular, in the case of the positive corona. This is because ozone is formed at the surface of the positive electrode as shown in Figure 6 and the ozone formation is highly dependent on ΔH_o (the highest standard heat of formation of oxides per oxygen atom) of the discharge electrode. In the case of a negative corona, on the other hand, ozone is formed apart from the discharge electrode and hence it shows little dependence on ΔH_o.

(2) The rate of the ozone emission by negative discharge is several times larger than that by positive discharge.

(3) The ozone emission is smaller at a thinner discharge electrode. Nashimoto[7] also qualitatively discussed these characteristics (2) and (3) for corotrons and assumed that the generation of ozone proportionally increases with an increase of the corona plasma volume around the discharge electrode. The present model also quantitatively supports this hypothesis.

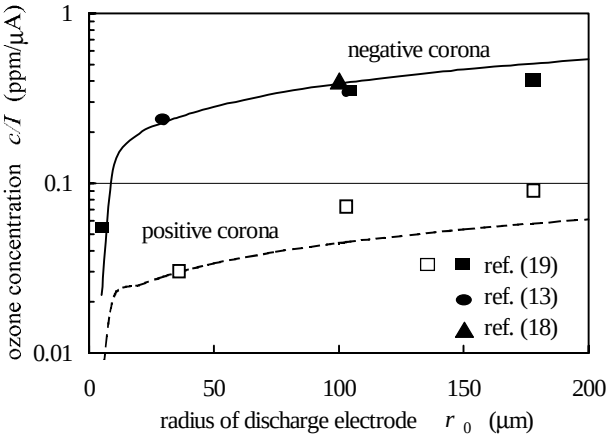

Figure 7. Measured and calculated ozone generation rate (Q = 1.5 liter/min).

Comparison with Corotron and Biased Contact Roller

The calculated ozone concentration is 63 ppm at 5 liter/min air flow rate for the corotron of a 30 μm radius wire made of tungsten under 400 μA total current which corresponds to the current to charge the typical photoreceptor of a low-speed (11 A4/min) A4-width laser printer.[11] It can be reduced to 1.4 ppm by adopting the biased contact roller.[11] On the other hand, it is only 0.46 ppm at the same condition by the charger with saw-tooth electrodes. The rate of ozone emission can be drastically reduced by use of the proposed charging system.

Concluding Remarks

A theoretical investigation has been performed to clarify ozone formation by the new electrophotography charger with saw-tooth electrodes. The following is a summary of the investigation.

Characteristics

The rate of the ozone emission by negative discharge is several times larger than that by positive discharge and in both cases the ozone emission is smaller at a thinner discharge electrode. This is because the generation of ozone proportionally increases with an increase of the corona plasma volume around the discharge electrode. It was confirmed by the numerical calculation that plasma volume of the positive corona is smaller than that of the negative corona. The ozone formation in the positive corona is highly affected by materials used for the discharge electrode, because, in the case of the positive corona, ozone is formed just at the surface of the discharge electrode. On the contrary, in the case of the negative corona, ozone is formed about 0.1 mm away from the electrode. Although the rate of ozone emission is nonlinear with respect to the discharge current, it is approximately linear within the usual design and operation conditions of electrophotography chargers.

Feasibility for Electrophotography Charger

The ozone generation rate of the 50 μm radius pin electrode is 0.085 ppm/μA under 5 liter/min air flow rate in case of negative corona. The ozone generation of the charger with saw-tooth electrodes is reduced to about one third of that with a biased charger roller and it is only 1/140 of that with the corotron. The rate of ozone emission can be drastically reduced by use of the saw-tooth electrodes compared with the corotron and the biased contact roller. The saw-tooth charger has a potential to realize the virtually ozone-free charger.

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Biography

Kawamoto, Hiroyuki holds a BS degree in Electrical Engineering from Hiroshima Univ. (1972) and a Dr. degree in Mechanical Engineering from Tokyo Institute of Technology (1983). From 1972 to 1991 he was a Senior Engineer at the Nuclear Division of Hitachi Ltd. In 1991 he joined Fuji Xerox, and was engaged in the research of electrophotography as a Research Fellow. In 1999 he left Fuji Xerox and he is now a professor of Waseda Univ. He is selected a Fellow of the IS&T in 1999.