Interfacial Force and Transfer Efficiency of Electrostatic Transfer Process in Electrophotography

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The electrostatic interfacial adhesive force acting on a spherical toner particle on a photoreceptor surrounded by a continuum toner layer was investigated. As the electric field of the toner layer is non-uniform, the variation in toner charge and the induced dipole and quadrupole moments on the spherical toner particle were obtained. The interfacial electrostatic force was calculated using the multiple effects of the mirror charge and the induced multiple mirror moments on the particle. The total interfacial force was obtained by adding a van der Waals force, as determined in relation to experimental results, to the electrostatic force. The efficiency of transferring a toner particle in intimate contact to paper saturated in the static state above a certain transfer voltage in the electrostatic transfer process. In the dynamic state, multiple phenomena related to toner particle transfer efficiency (saturation, plateau, peak, and impossible of detachment) were explained by the influence of toner charge. These phenomena resulted from variations in the threshold detachment field due to variations in the toner charge. It was shown by centrifugal experiment, that the force depends on $R^{2.2}$ for radius, R, of toner particle, and these results explain various experimental observations on the electrostatic transfer process.

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Introduction

In order to realize high quality printing in electrophotography, improvements in the electrostatic transfer process (ETP) have been required. Use of small toner particles has been proposed for elimination of edge raggedness on the toner image during ETP. The edge raggedness, except for mechanical reasons, was found to be related to Paschen's discharge in the non-image white area which affects the edges of the toner image area in ETP.[1] However, fundamental and unresolved problems have remained in ETP, and the application of a toner with small particle size is closely related to these problems. The first problem is transfer efficiency (η): the efficiency reaches a peak, and then decreases with increasing applied transfer voltage (Vt).[2] The second one is residual toner on the photoreceptor after ETP[3,4]: transferring small toner particles from the photoreceptor to paper is difficult, so that the contribution of such toner to high quality printing is minimal. This is a common problem for handling small particles.[3,4] These phenomena are easily observed in electrophotography, however, systematic analysis has been lacking for over two decades. The third problem is the detachment force of the toner particles in intimate contact with the photoreceptor, and a large difference between the forces measured in a parallel electrode experiment (PEE) and in a centrifugal force experiment (CFE) has been reported: the detachment force in CFE is five to fifty times larger than that in PEE.[5]

Recently, analytical closed form solutions for the voltage in a one-dimensional continuum model which corresponds to the four-layer state (photoreceptor- toner layer- paper - transfer belt) were obtained for ETP.[1] It was found out by this analysis that an electrostatic transfer field E applied on a toner particle surrounded by other toner particles in the toner layer is not constant, and shows position and time dependences. Accordingly, this field is a non-uniform electric field and has a properties of div $E \neq 0$ in the toner layer, so that variation in the toner charge density (ρ) with an influence factor (λ) on application of Vt was obtained using Maxwell's equations. This means that the induced dipole ($p_{ex}^{(1)}$) and quadrupole ($p_{ex}^{(2)}$) moments on a toner particle are naturally obtained.[6,7] On the other hand, the measurements of detachment force in PEE have been done at dilute toner density, to facilitate counting the number of toner particles before and after the experiment; in that case then the electric field in the toner layer was taken as the field in the air gap layer, which is constant and uniform across the toner layer. This gives div E = 0; thus conventional PEEs are different from the actual ETP.

This article deals with the above three problems. In the first section, the electric field applied by surrounding toner and the transfer voltage Vt on a toner particle in the toner layer is obtained by the method of the previous study.[1] This field depends on the position of the toner particle, and has non-uniform properties. Therefore, the

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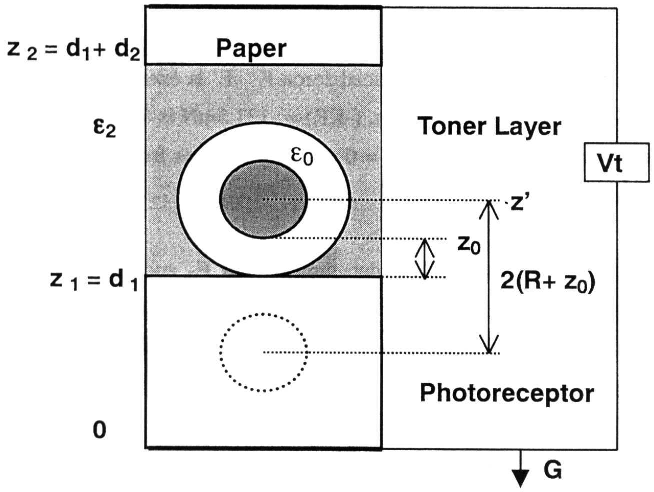

Figure 1. Schematic illustration of spherical toner particle surrounded by toner layer during the electrostatic transfer process. Dotted circle in the photoreceptor is the mirror image of the toner particle.

dielectrophoretic force, which is the interfacial electrostatic force between the toner particle and photoreceptor is obtained by the method of calculation of Jones,[6] and Fowlkes and Robinson.[7] The final form of the dielectrophoretic force for the toner particle is given by Eq. (18). This force depends on the electric field that is applied to the toner particle, the toner charge, and the properties of toner layer. In the second section, nonelectrostatic van der Waals force is included in addition to the dielectrophoretic force in Eq. (19) for the toner particle in intimate contact with the photoreceptor. The minimum van der Waals force is proposed by the condition, where static transfer efficiency does not show $\eta = 1$. The total interfacial force is then a second order function of E, so that the force is attractive or repulsive according to the magnitude of the electric field, E. This analysis gives the threshold detachment field, designated $E\pm$, and $E\pm$ is compared with the electric field applied on a toner particle in the toner layer, which is denoted by E'. Detachment of the toner particle in intimate contact requires the repulsive force which is obtained by the condition $|E-| < |E'| < |E+|$. In the static state, which is defined by $\lambda = 0$ and $\Delta V_2(t) = 0$, the relationship of the transfer efficiency (η) versus the transfer voltage (Vt) exhibits saturation even at high Vt. The dynamic state is investigated in the third section and we show that the above three problems for ETP depends thereby on the toner charge influence factor λ. According to the usual experimental observation, the above three problems are commonly related to the narrow range of λ. For the case of $\lambda \cong 0.42$, η shows a peak versus Vt, and detachment of small toner particles is impossible in ETP. The case of $\lambda \cong 0$ is similar to the static state and in the state of $\lambda > 0.5$, detachment of the intimate contact toner particle is difficult. In the final section, discussion and conclusions are given, along with a schematic illustration of the total interfacial force for the toner particle in intimate contact with the photoreceptor.

Electrostatic Force for Interfacial Toner

A model for ETP is shown in Fig. 1. For simplicity, it has only three layers: photoreceptor, toner layer, and paper. The toner layer surrounds an isolated spherical toner particle in a thin air cavity, which is adjusted by the packing (volume) fraction P in the toner layer after the development process. In this mode, this air gap does not specify a geometrical structure of the toner layer. A separation distance between the surface of the toner particle and the photoreceptor is z_o, and for the case of $z_o \leq 10$ nm, we define intimate contact of the toner particle with photoreceptor. The dynamic voltage distribution in the toner layer is given by Eq. (1).[1] The toner layer is given by toner charge (volume) density ρ_0 which is specified by P, electric permittivity $\varepsilon_2 = \kappa\,\varepsilon_0$, where ε_0 is the permittivity of air, and thickness d_2. The voltage of the rear surface of the paper is equal to Vt, and the coordinate is selected in the one-dimensional z direction.

$$\phi_2(z,t) = \phi_2(z) - \lambda\Delta V_2(t)\,(z-z_2)^2/d_2^2 + (1-\lambda)\Delta V_2(t)\,(z-z_2)/d_2 + \Delta V_1(t) + \Delta V_2(t), \qquad (1)$$

where

$$\phi_2(z) = Vt - (\rho_0/2\varepsilon_2)(z-z_2)^2 + H(z-z_2)/(\varepsilon_2\Sigma D) - H\gamma,$$
$$\Sigma D = D_1 + D_2 + D_3,\ \alpha = D_1/\Sigma D,\ \beta = D_2/\Sigma D,\ \gamma = D_3/\Sigma D,$$
$$\alpha + \beta + \gamma = 1,\ H = Vt - Va - \rho_0 d_2(D_1 + D_2/2), \qquad (2)$$
$$\Delta V_j(t) = V_j(t) - U_j,\ \ U_2 = (H\beta + \rho_0 d_2 D_2/2),$$
$$\rho_0 = (Q_0/m)\,\rho_g P = (3Q_0/4\pi R^3)P = (3\sigma_0/R)P.$$

In these notations, $D_j = (d_j/\varepsilon_j)$ is the dielectric thickness of each layer ($j = 1$ is the photoreceptor; $j = 2$, the toner layer; $j = 3$, the paper). $\Delta V_2\,(t)$ is defined by the difference between dynamic $V_2\,(t)$ and static voltage difference U_2 across the toner layer.[1] Q_0 is the electric charge, m is the mass, ρ_g is the mass density, and σ_0 is the surface charge density for the toner particle at the initial state. R is the radius of a spherical toner particle.

The ideal transfer efficiency,[1] which is the efficiency when there is no interfacial adhesive force, is denoted by η_0; the applying transfer voltage Vt is expressed by Eq. (3) of η_0 throughout this paper, where Va is the voltage of the imaged area on the photoreceptor and Vb is the bias voltage on the development. These notations are given in detail in the previous study.[1]

$$\eta_0 = -H/\rho_0 d_2\Sigma D,$$
$$Vt = Vb - \eta_0\,\rho_0 d_2 \Sigma D, \qquad (3)$$

where

$$Vb = Va + \rho_0 d_2(D_1 + D_2/2).$$

The interfacial electrostatic force for the spherical toner particle results from the electric field of the toner layer, mirror image force between the toner and photoreceptor, and the effect of induced multiple moments on the toner particle. According to the study of Jones,[6] the generation of induced multiple moments ($p^{(n)}$) and electrostatic forces on the toner particle ($F(z)$), which is called as the dielectrophoretic force, are given in a nonuniform electric field, and expressed by next equations.

$$p^{(n)} = [(\varepsilon_2 - \varepsilon_0)g(n)\,R^{2n+1}/\Omega n!][d^{n-1}E/dz^{n-1}], \qquad (4)$$

$$F(z) = \Sigma\,(p^{(n)}/n!)\,d^nE(z)/dz^n, \qquad (5)$$

where

$$g(n) = n/[n\varepsilon_2 + (1+n)\varepsilon_0] \text{ and } \Omega = 1/4\pi\varepsilon_0.$$

Using Maxwell's equations in Eq. (1); $E(z,t) = -\text{grad}\ \phi_2(z, t)$, and div $E = (\rho/\varepsilon)$, the next equations are obtained, where the direction of the vector is positive or negative, owing to the one dimensional calculation. This electric field is the applied electrostatic transfer field on a toner particle surrounded by other toner particles in the toner layer, and depends on position and time.

$$
\begin{aligned}
E_2(z,t) &= (\rho_0/\varepsilon_2)(z - z_2) - H/\varepsilon_2 \Sigma D + 2\lambda \Delta V_2 (z - z_2)/d_2^2 - \\
&\quad (1 - \lambda)\Delta V_2/d_2, \\
dE_2/dz &= (\rho_0/\varepsilon_2) + 2\lambda \Delta V_2/d_2^2, \\
d^2E_2/dz^2 &= 0. \qquad (6)
\end{aligned}
$$

When Vt is applied to the toner layer, induced dipole ($p_{ex.}^{(1)}$) and quadrupole ($p_{ex.}^{(2)}$) moments on the toner particle generate according to Eqs. (4) and (6). The variation in toner charge density is also given by

$$\rho = \rho_0(1 + X), \text{ where } X = [2\ \lambda\ \Delta V_2(t)/\rho_0 d_2 D_2], \qquad (7)$$

and is related to the toner charge Q and the surface charge density σ:

$$\rho/\rho_0 = Q/Q_0 = \sigma/\sigma_0 = (1 + X). \qquad (8)$$

The electric fields at the interface z_1 and z' are given by Eq. (9). The coordinate of the center of the toner particle is z', and z' is expressed by $\chi = (z_0/R)$, where the position of $z_0 \cong 10$ nm for the intimate contact toner particle is treated by $\chi = 0$.

$$
\begin{aligned}
E_2(z_1,t) &= \rho_0 D_2(\eta_0 - 1) - (1 + \lambda)\Delta V_2/d_2, \\
E_2(z',t) &= E_2(z_1,t) + (1 + \chi)(\rho_0 R/\varepsilon_2)(1 + X), \qquad (9) \\
&= E_2(z_1, t) + (1 + \chi)(3P/\kappa)(\sigma/\varepsilon_0),
\end{aligned}
$$

where

$$z_1 = d_1 \text{ and } z' = R + z_0 + d_1 = R(1 + \chi) + d_1.$$

The following notations are used in the calculation of the dielectrophoretic force.

$$
\begin{aligned}
a &= g(1)(\varepsilon_2 - \varepsilon_0), \qquad b = [g(1)(\varepsilon_2 - \varepsilon_0)/(1 + \chi)^3], \\
c &= [g(1)(\varepsilon^2 - \varepsilon_0)^2/(1 + \chi)^4], \qquad (10) \\
d &= [(\varepsilon_2 - \varepsilon_0)/(1 + \chi)], \qquad e = [g(2)(\varepsilon_2 - \varepsilon_0)/(1 + \chi)^2].
\end{aligned}
$$

Coulomb force on a toner particle is $F_1 = QE_2$. From Eqs. 2 and 10, the interaction (F_2) between E_2(z) and the induced moments ($p_{ex.}^{(n)}$) is given by

$$F_2 = (3P/\kappa)\ aQE_2. \qquad (11)$$

The mirror moments ($p_{ex.\ m}^{(n)}$) of $p_{ex}^{(n)}$ induced in the photoreceptor, which is treated as a conducting plate, are obtained, according to Fowlkes and Robinson.[7]

$$p_{ex.\ m}^{(n)} = (-1)^{n+1}\ p_{ex}^{(n)}. \qquad (12)$$

The electric field, $E_{m.1}$, at the position of toner particle and created by image charge ($-Q$) and $p_{ex.m}^{(n)}$ is obtained, and the interaction (F_3) between $E_{m.1}$ and toner charge Q is given by,

$$F_3 = [-\Omega Q^2/4R^2(1 + \chi)^2][1 + (3P/\kappa)(3e/8)] + bQE_2/4. \ (13)$$

TABLE I. Coefficients of Interfacial Electrostatic Force: P = 0.5, and κ = 1.7.

χ	0	0.1	0.2	0.3	0.4	0.6	0.8	1.0
A	1.51	1.17	0.94	0.78	0.66	0.49	0.38	0.31
B	1.3	1.26	1.24	1.22	1.21	1.2	1.19	1.18
C	0.068	0.043	0.03	0.02	0.015	0.009	0.005	0.004

The interaction (F_4) between $dE^n_{m.1}/dz^n$ and $p_{ex.}^{(n)}$ is obtained by,

$$
\begin{aligned}
F_4 &= (bQE_2/4)[1 + (9e\ P/2\kappa)] - (3/8\Omega)\text{cg}(1)R^2E^2_2 \\
&\quad - [9\Omega\ ePQ^2/32\kappa R^2(1 + \chi)^2](1 + 15eP/4\kappa). \qquad (14)
\end{aligned}
$$

From Eq. (4), $\mu_1^{(n)}$ of the multiple moments ($\mu_1^{(n)}$) induced on the toner particle by the electric field $E_{m.1}$ is

$$\mu_1^{(1)} = [-aQR/4(1 + \chi)^2](1 + 9eP/8\kappa) + (abR^3/4\Omega)E_2. \ (15)$$

The interaction (F_5) between dE_2/dz and $\mu_1^{(1)}$ is given by,

$$
\begin{aligned}
F_5 &= [-\ 3a\Omega PQ^2/4\kappa\ R^2(1 + \chi)^2][1 + (9eP/8\kappa)] \\
&\quad + (3abPQE_2)/4\kappa. \qquad (16)
\end{aligned}
$$

Using Eq. (5), the interaction (F_6) between $d^nE_{m.1}/dz^n$ and $\mu_1^{(n)}$ is obtained. The mirror multiple moments ($\mu_{1.m}^{(n)}$) in the photoreceptor are given by $\mu_{1.m}^{(n)} = (-1)^{n+1}\mu_1^{(n)}$, and the electric field $E_{m.2}$ on the toner particle generates, in a similar manner to $E_{m.1}$. The interaction (F_7) between $E_{m.2}$ and Q is given by $F_7 = QE_{m.2}$. The interaction (F_8) between $p_{ex}^{(n)}$ and $d^nE_{m.2}/dz^n$ is also obtained. The multiple moments induced on the toner particle due to $E_{m.2}$ are denoted by $\mu_2^{(k)}$, and the interaction between (dE_2/dz) and $\mu_2^{(1)}$ is given by $F_9 = \mu_2^{(1)}(dE_2/dz)$. Finally, the interaction (F_{10}) between $\mu_2^{(k)}$ and ($d^kE_{m.1}/dz^k + d^kE_{m.2}/dz^k$) is obtained. However, because the force, F_{10}, is very small compared with the other forces, it may be neglected. The total interfacial electrostatic force on the toner particle is given by Eq. (17) and in the Appendix.

$$
\begin{aligned}
F &= Q\ (E_2 + E_{m.1} + E_{m.2}) + p_{ex}^{(1)} d/dz\ (E_2 + E_{m.1} + E_{m.2}) \\
&\quad + (p_{ex}^{(2)}/2)\ d^2/dz^2\ (E_{m.1} + E_{m.2}) + (\mu_1^{(1)} + \mu_2^{(1)})(dE_2/dz) \\
&\quad + \Sigma\ (\mu_1^{(n)}/n!)(d^nE_{m.1}/dz^n). \qquad (17)
\end{aligned}
$$

This force is expressed in Eq. (18), wherein the physical properties of the toner particle (κ, P) and the electric field, E ($d^nE/dz^n \neq 0$), are reduced to the coefficients A, B, and C, and the force is determined by charge Q, radius R, and magnitude E in the interfacial state:

$$F = -A\ (Q^2/16\pi\varepsilon_0 R^2) + BQE - C(\pi\varepsilon_0 R^2E^2). \qquad (18)$$

Coefficients A, B, and C for P = 0.5 and κ = 1.7 are summarized in Table I.

Static Interfacial Force and Transfer Efficiency

The static state of ETP is specified by $\lambda = 0$ and $\Delta V_2(t) = 0$ in Eq. (6), which shows the initial state on application of Vt.[1] The force given in Eq. (18) does not include the non-electrostatic interfacial force, which is typically known as the van der Waals adhesive force. This force becomes dominant within a certain separation distance ($z_0 \leq 10$ nm).[3,7,8] The force is expressed as KR and is proportional to the radius of toner particle,[3] so that the total interfacial force between the intimate contact toner particle and the photoreceptor is given by next Eq. (19).

$$F(z_1) = -KR - A\,(Q^2/16\pi\varepsilon_0 R^2) + BQE(R) - C\pi\varepsilon_0 R^2 E^2(R): \quad z_0 \leq 10 \text{ nm}. \tag{19}$$

Consequently, Eq. (18) corresponds to the non intimate contact between toner particle and photoreceptor, $z_0 > 10$ nm. The electric field for the toner particle is determined by the center position of the spherical toner, and Eq. (19) is treated as a second order function of E. The detachment of the intimate contact toner particle requires a repulsive force. The range of the repulsive force is obtained by calculating the real solutions corresponding to $F = 0$ in Eq. (19). We call these real solutions the threshold detachment fields (E_+ and E_-). The transfer range of the electric field (E') applied on the toner particle is limited by the condition of $E_+ \leq E' \leq E_- < 0$ because of toner charge $Q_0 < 0$ in this paper. We used numerical parameters of $R = 5$ µm, $P = 0.5$, $(Q_0/m) = -35$ µC/g, and $\rho_g = 1.2$ g/cm^3, so that $\rho_0 = -21$ C/m^3, $Q_0 = -2.2 \times 10^{-14}$ C, $\sigma_0 = -7 \times 10^{-5}$ C/m^2, and $(\sigma_0/\varepsilon_0) = -7.91$ V/µm, in order to be consistent with the previous study.[1]

The threshold detachment fields and the maximum force of Eq. (19) are obtained by

$$E_\pm(R) = (2B/C)(\sigma/\varepsilon_0)\{1 \pm [1 - (C/4B^2)(A + 4KR\varepsilon_0/\sigma Q)]^{1/2}\}, \tag{20}$$

$$Fmax = (\sigma/\varepsilon_0)Q(B^2/C - A/4) - KR, \text{ at } E = (2B/C)(\sigma/\varepsilon_0), \tag{21}$$

and using the approximation

$$E_+(R) \cong (B/C)(\sigma/\varepsilon_0)[4 - (C/4B^2)(A + 4KR\varepsilon_0/\sigma Q)],$$
$$E_-(R) \cong (1/4B)(\sigma/\varepsilon_0)(A + 4KR\varepsilon_0/\sigma Q). \tag{22}$$

For $z_0 > 10$ nm, the threshold detachment fields $E\pm(R)$ and $Fmax$ for the static state are given by $\chi = 0$ in Table I, and $KR = 0$ in Eqs. (20) and (21): $E_+(R) = -602.1$ V/µm, $E_-(R) = -2.31$ V/µm, and $Fmax = 4.25$ µN.

In conventional experiments,[2] a transfer efficiency $\eta = 1$ is impossible. We propose that the detachment of the intimate contact toner particle ($z_0 \leq 10$ nm) is difficult at Vt corresponding to $\eta_0 = 1$ in Eq. (3) for the static state. This condition corresponds to $E_- \leq E' \leq 0$. The applied electric field at the center of the intimate contact toner particle is obtained using Eq. (9): $E'(R) = (3P/\kappa)(\sigma_0/\varepsilon_0)$, because of $E_2(z_1) = 0$ and $\chi = 0$. Applying the condition of $E_- \leq E'$ to Eq. (20), it is found out that the van der Waals force KR for $R = 5$ µm is restricted:

$$KR \geq Q_0(\sigma_0/\varepsilon_0)[B(3P/\kappa) - (C/4)(3P/\kappa)^2 - A/4] = 131.5 \text{ nN}, \quad \text{and } K = 26.3 \text{ nN/µm}. \tag{23}$$

Iimura and co-workers[9] measured the interfacial adhesive force of non-charged toner particles using CFE and obtained a KR of about 110 nN for the toner particle of $R = 5$ µm. As the van der Waals force decreases with increasing surface roughness,[3,9] and KR of 131.5 nN corresponds to a perfect sphere, the KR estimated here is in good agreement with the observation of CFE.[9] A coefficient K of 26.3 nN/µm is located within the values evaluated by Goel and Spencer.[3] They obtained the coefficients between the photoreceptor and toner particle according to dispersion theory using the parameter z_0, without any deformation of the toner particle. Accordingly, we use the minimum value of $-KR = -131.5$ nN for $R = 5$ µm and $K = 26.3$ nN/µm as the non-electrostatic interfacial adhesive force throughout this article.

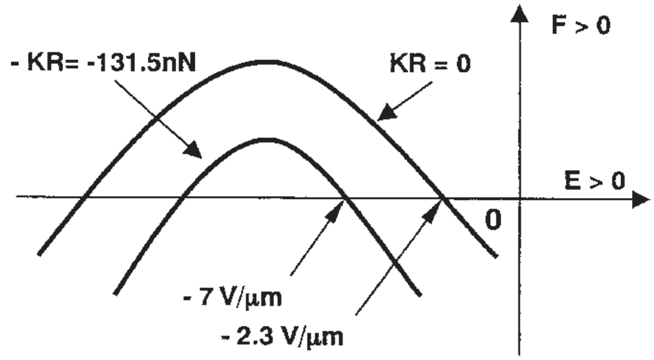

Figure 2. Schematic illustration of static interfacial force F. E' is applied field. KR is van der Waals force. $KR = 0$ corresponds to $z_0 > 10$ nm. $(-KR) = -131.5$ nN is the case of $z_0 \leq 10$ nm for $R = 5$ µm. Threshold electric fields, E^-, on $F = 0$ abruptly changes from -2.3 to -7 V/µm, with decreasing of z_0 from $z_0 > 10$ nm

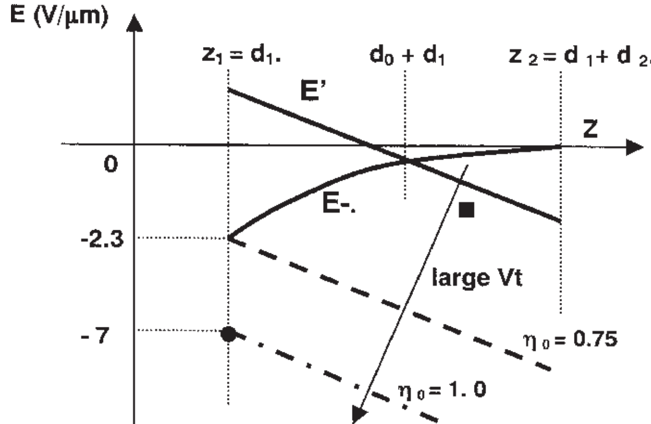

Figure 3. Schematic relation between threshold detachment field, E_-, and applied field, E', for static state. z_1 and z_2 are the interfacial positions of photoreceptor–toner and toner–paper, respectively. Transfer condition of negative charge toner is $E' < E_- < 0$, and toner layer between $(d_0 + d_1)$ and z_2 is transferred to paper

The threshold detachment fields $E_\pm(R)$ and $Fmax$ for $z_0 \leq 10$ nm can also be obtained using Eqs. (20) and (21) for $KR = 131.5$ nN: $E_+(R) = -597.4$ V/µm, $E_-(R) = -6.97$ V/µm and $Fmax = 4.12$ µN. A schematic illustration of the interfacial force F versus $E(R)$ for $KR = 0$ and 131.5 nN in the static state is shown in Fig. 2. When the position of the toner particle in the toner layer changes from $z_0 > 10$ nm to $z_0 \leq 10$ nm, the threshold detachment field, E_-, also abruptly changes from -2.31 to -6.97 V/µm, because the interfacial non-electrostatic force changes from $KR = 0$ to $KR = 131.5$ nN.

The values of $E-$ for $\chi \neq 0$ and $KR = 0$ are also easily evaluated and shown schematically in Fig. 3, where $E'(z)$ is the applied field given by Eq. (9). The detachment condition is satisfied by the region between $(d_0 + d_1)$ and z_2 of the toner layer and the transfer efficiency η is determined by $(d_2 + R - d_0)/d_2$, because d_0 is the center of the toner particle. As Vt is increased, η becomes larger, however η saturates and becomes the constant at the value of Vt where $\eta_0 > 0.746$, in the region between dotted and dashed lines. This is because the detachment of the intimate contact toner particle ($z_0 \leq 10$ nm) requires a Vt of $\eta_0 \geq 1$ for $E'(R) \leq -7$ V/μm, for the case of a spherical toner with $R = 5$ μm. Practically, toner particles have a wide distribution of size, so that KR is also widely distributed. As the transfer efficiency η of the static state only shows the saturation in high Vt, the three problems mentioned in the Introduction are still unresolved. Accordingly, we investigate the dynamic state in next.

Dynamic Interfacial Force and Transfer Efficiency

The dynamic state of ETP is specified by $\lambda \neq 0$ and $\Delta V_2 \neq 0$ in Eq. (6). The dynamic voltage difference across the toner layer for the three layer structure is given by the following equations,[1] where τ_2 and τ_3 are the time constants of the toner and paper layers, respectively.

$$V_2(t) = B_2 \exp(-\mu t) + B_3 \exp(-\zeta t),$$

$$\text{where} \quad \mu = (1/\tau_0 - \omega\, \tau_0),\ \zeta = \omega\, \tau_0, \tag{24}$$

$$\text{and} \quad 1/\tau_0 = (1-\beta)/\tau_2 + (1-\gamma)/\tau_3,\ \omega = \alpha/(\tau_2\, \tau_3).$$

Coefficients B_2 and B_3 are given by,

$$B_2 = (j\, U_2 - U_3)/(j-h),\ B_3 = (-hU_2 + U_3)/(j-h),$$

$$\text{and } B_2 + B_3 = U_2, \tag{25}$$

$$\text{where} \quad U_2 = \rho_0\, d_2 D_2\left(\frac{1}{2} - \eta_0\right),\ U_3 = -\eta_0\, \rho_0 d_2 D_3,$$

$$\text{and} \quad j = (\tau_3/\beta\tau_2)(1 - \beta - \mu\tau_2),\ h = (\tau_3/\beta\tau_2)(1 - \beta - \zeta\tau_2).$$

The Vt off state, which is specified by $Vt = 0$ after ETP of transfer time t_0, is given by

$$V'_2(t) = V_2(t) - C_2 \exp(-\mu t') - C_3 \exp(-\zeta t')\ ;\ t' = t - t_0,$$

$$\text{where } C_2 = Vt\,(j\,\beta - \gamma)/(j-h),\ C_3 = Vt\,(\gamma - h\,\beta)/(j-h),$$

$$\text{and} \quad C_2 + C_3 = \beta Vt. \tag{26}$$

We suppose that the paper is separated from the photoreceptor immediately after the Vt off state ($t = t_{0+}$) and that the transfer efficiency η is observed immediately. Accordingly,

$$\Delta V_2 = V'_2(t_0) - U_2 = V_2(t_0) - \beta Vt - U_2. \tag{27}$$

From Eqs. (7), (8), (22), and (27), the threshold detachment field for the dynamic state is obtained by

$$E-(R, t_0) = (A/4B)(\sigma_0/\varepsilon_0)(1 + X) + KR/[BQ_0(1 + X)]. \tag{28}$$

while the field applied on the intimate contact toner particle is obtained from Eq. (9):

$$E'(R, t_0) = (3P/\kappa)(\sigma_0/\varepsilon_0)[1 + (d_2/R)(\eta_0 - 1)]$$
$$- (\Delta V_2/d_2)\{1 + \lambda\,[1 - (2R/d_2)]\}. \tag{29}$$

The dynamic variation in $E-(R, t_0)$ depends on the variation in the toner charge. The variation in $E'(R, t_0)$ results from ΔV_2.

Values of $E_-(R, t_0)$ and $E'(R, t_0)$ for the intimate contact toner particle with $R = 5$ μm are shown in Fig. 4, for $\tau_2 = 830$ msec,

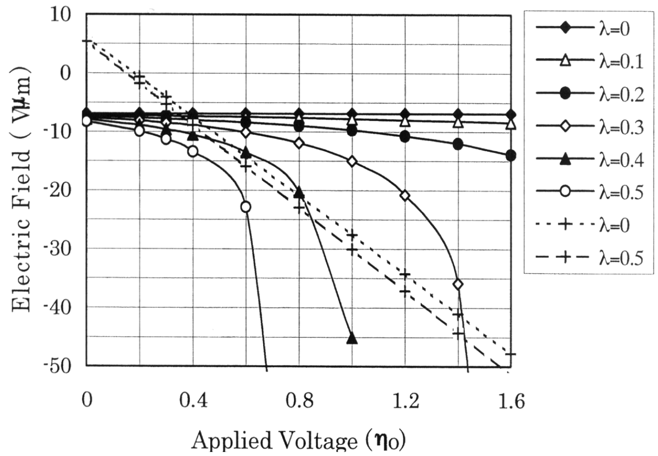

Figure 4. Threshold detachment field, E, and applied field, E', as a function of transfer voltage, for dynamic state and R = 5 μm. Solid line indicate threshold field E(V/μm), and straight dotted and dashed lines are E' (V/μm). λ is an influence factor for the variation in toner charge. The choice of $\lambda \leq 0.4$ satisfies the transfer condition, $E' < E < 0$.

$\tau_3 = 9.3$ msec, $\mu = 0.0324$/msec, $\zeta = 4.95 \times 10^{-4}$ msec^{-1}, $j = 0.02755$, $h = -1.704$, $d_2 = 13.2$ μm, $\Sigma D = 45.43$ μm/ε_0, $\beta = 0.171$, and $\gamma = 0.704$. The transfer time is $t_0 = 50$ msec, and Vt is expressed by η_0 using Eq. (3). The solid lines are the threshold detachment fields $E-(R)$ and dotted lines are the applied fields $E'(R)$. The dotted lines are expressed by a narrow band, while the solid lines show that $E-(R)$ greatly depends on the charge influence factor λ. Based on the transfer condition of $E' \leq E- < 0$ used for Fig. 4, in the region $\lambda < 0.2$, the the intimate contact toner particle is detached from the photoreceptor when $\eta_0 > 0.35$, and the transfer efficiency η saturates. This behavior is similar to the static state, however the detachment range of η_0 in the dynamic state expands compared with that in the static state. The transfer efficiency η for $\lambda = 0.3$ is expressed by the shape of plateau for an increasing η_0 ($\propto Vt$), and the intimate contact toner particle does not detach from the photoreceptor at higher values of Vt. For $\lambda = 0.4$, a peak in η appears with increasing Vt, and for $\lambda > 0.5$, detachment of the intimate contact toner particle with $R = 5$ μm becomes impossible.

We investigate the dependence of the radii of the intimate contact toner particles. We set $\lambda = 0.42$ in order to obtain correspondence with the experiment,[2] and set Q_0/m to a constant value, which means ρ_0 is constant for the radii of toner particles according to Eq. (2). Based on Eqs. (28) and (29) and the transfer condition, the detachment range of η_0 for each radius is obtained as shown in Fig. 5, where $E(4)$ and $E'(4)$ express the threshold detachment field and the applied field of $R = 4$ μm, respectively.

The threshold detachment fields for the static and dynamic states of $\eta_0 = 0$ and 0.5 are listed in Table II. Remarkably, a small toner particle shows a large negative E_- and a small $Fmax$, and vice versa. These results indicate that the detachment of toner with small particle site requires a large negative applied field $E'(R)$ compared to that required by toner with large particles. Hays[5] surveyed many measured values of the detachment field, which are close to those shown in Table II in spite of different experimental conditions.

Figure 5 shows that detachment of the intimate contact toner particle for $R = 4$ μm is impossible and that

TABLE II. Threshold Detachment Field, Maximum Interfacial Force and Detachment Range of η_0 for constant Q_0/m : $\rho_0 = {}^-21C/m^3$, $\lambda = 0.42$, and $\chi = 0$.

R	Q_0	σ_0	E_- (static)	E_- ($\eta_0 = 0$)	E_- ($\eta_0 = 0.5$)	$Fmax$	Detachment range
4	– 1.1	– 56	– 9	– 11	– 18.7	1595	impossible
5	– 2.2	– 70	– 7	– 7.9	– 13.3	4121	$0.51<\eta_0<0.77$
6	– 3.8	– 84	– 6	– 6.3	– 9	8649	$0.35<\eta_0<0.91$
6.6	– 5.1	– 92.4	– 5.7	– 5.8	– 7.8	12727	$0.28<\eta_0<0.95$

R: μm, Q_0: x10^{-14}C, σ_0: μC/m^2, E_- : V/μm, $Fmax$: nN.

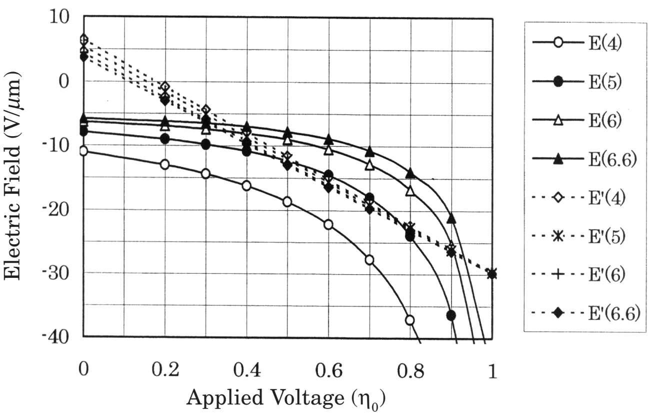

Figure 5. Threshold detachment field, E, and applied field, E', as a function of transfer voltage, for dynamic state where $\lambda = 0.42$ and Q_0/m = constant. Solid lines indicate threshold field E(V/μm), and straight dotted and dashed lines are E' (V/μm). Index 4, e.g., $E(4)$ and $E'(4)$, denotes the electric fields for the case, R = 4 μm. The transfer condition is $E' < E < 0$.

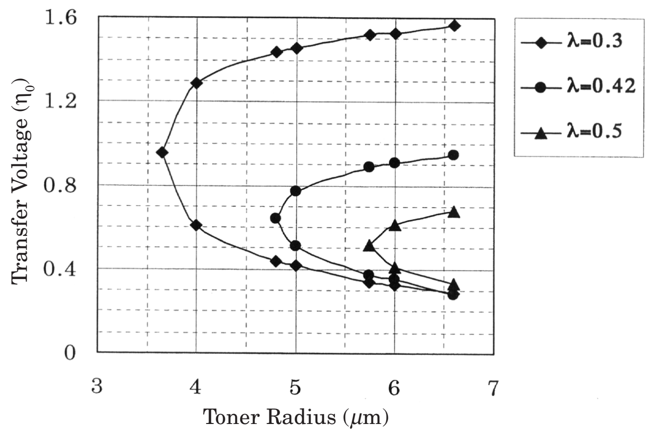

Figure 6. Relation between transfer voltage and radius of toner particle for dynamic state of Q_0/m = constant. For a constant R, the detachment of intimate contact toner particle is possible for the values of η_0 between an upper and a lower limiting radius.

the detachment range of η_0 for $R \geq 5$ μm expands from a mean value of η_0 about 0.64 with increasing of the radius of toner particle. As the toner particles have a wide distribution of radius experimentally, this indicates that small toner particles stay on the photoreceptor, while large particles are easily removed during ETP. As the mean value of η_0 is common for the radii of toner particles, the transfer efficiency η expected in experiment shows a peak at the mean transfer voltage.

Figure 6 shows the relation between the applied transfer voltage η_0 ($\propto Vt$) and radius of toner particle for various λ. For a certain radius and λ, the detachment range of the transfer voltage on the interfacial toner is enclosed by the values of η_0 between an upper and a lower η_0. For a small λ, (0.3), the toner particle with a radius larger than about 4 μm is detached with the mean value of η_0 about 0.94, and the transfer efficiency η versus Vt is observed as a plateau shape. However, for $\lambda = 0.5$, only toner with particles larger than about 6 μm is transferred from the photoreceptor. The detachment range of the transfer voltage with a mean η_0 of about 0.51 becomes narrower than with the small λ, and the transfer efficiency η shows a sharp peak against Vt. Therefore, as illustrated by Figs. 4, 5, and 6, the multiple phenomena of transfer efficiency η (saturation, plateau, peak, and impossible detachment of small toner particle) versus Vt are explained with the parameter λ. The results shown in Fig. 6 agree well with various experimental results of ETP, reflecting a wide distribution of toner particle radius, charge, shape, electric permittivity, packing ratio, and time constant.

Next, we consider the experimental conditions of CFE and PEE. There are two situations for explaining CFE: (1) the applied field $E'(R) = 0$, and (2) $E'(R) \neq 0$, when the transfer voltage $Vt = 0$ and transfer time $t_0 = \infty$, because the time necessary for a centrifuge to reach its full speed is a few minutes even if an ultracentrifuge machine.[3,9,10] These situations relate to the applied field on the intimate contact toner particle due to the surrounding toner layer. The first situation corresponds to the experimental condition of monolayer toner coverage and enough dilute density on the photoreceptor, namely $P \cong 0$, so that the electrostatic interaction among toner particles is very weak. On the other hand, the second situation is identified with a dense coverage of toner particles and/or multiple toner layers which result in an electric field, $E'(R) \neq 0$ even if $Vt = 0$. The second situation is expressed by the η_{00} of $Vt = 0$, using Eqs. (3), (24), and (27):

$$\eta_{00} = Vb/(\rho_0 d_2 \Sigma D)$$
$$\Delta V_2(\infty)/d_2 = -U_2/d_2 = \rho_0 D_2\left(\eta_{00} - \tfrac{1}{2}\right), \tag{30}$$

The field applied to the intimate contact toner particle with η_{00} is given by Eq. (9), so that

$$E'(R,\infty) = [(2R - d_2)/d_2][(\rho_0 D_2/2)(1 - \lambda) + (\lambda V_b/\varepsilon_2 \Sigma D)]. \tag{31}$$

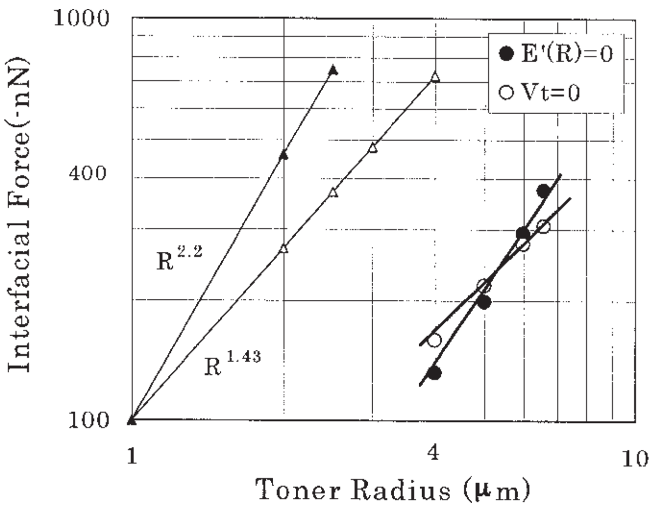

Figure 7. Calculated interfacial adhesive forces corresponding to centrifugal force experiment where Q_0/m = constant. Triangles indicate illustrating various powers of R.

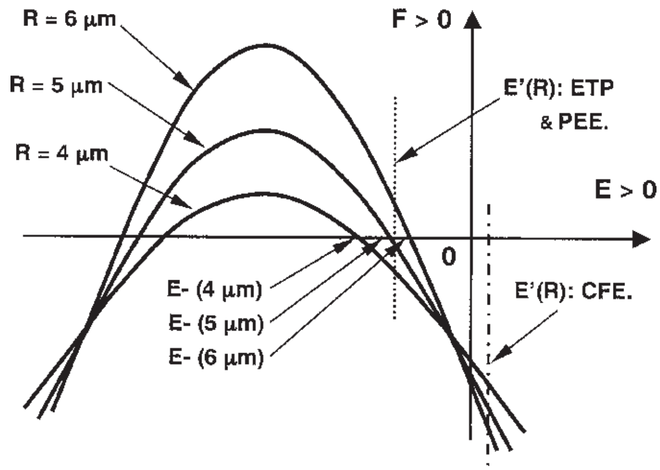

Figure 8. Schematic illustration for interfacial force F as a function of electric field E. The electric fields for the electrostatic transfer process (ETP) and parallel electrode experiment (PEE) are a little larger than threshold field E^-. The centrifugal force experiment (CFE) is approximated by $E \cong 0$.

The first situation for CFE is obtained where $2R\ d_2$, $\rho_0 \cong 0$ and $Vb \cong a$ due to $P \cong 0$ in Eq. (31). The interfacial adhesive force for CFE is evaluated by Eqs. (19) and (31) with $\lambda = 0.42$ and $\chi = 0$, and shown in Fig. 7. The mirror image force which is the second term in Eq. (19) increases with R^4 when Q_0/m is constant, and dominates the total adhesive force where $R >$ 6.4 μm with the present parameter values. The resultant forces for CFE with $\lambda = 0.42$ increase with the radius of the toner particle; the powers of R for $E'(R) = 0$ and $E'(R) \neq 0$ on $Vt = 0$ are represented by $R^{2.2}$ and $R^{1.43}$, respectively. Accordingly, the detachment of a large toner particle requires a large centrifugal force, and vice versa. This behavior is opposite to that of ETP, where the detachment of a small toner particle requires large negative E_-(R) and ultimately become impossible, as shown in Fig. 5 and Table II. This means that the present evaluation starting from Eq. (19) can explain the differing results between ETP and CFE.

Noguchi and co-workers[10] measured the interfacial adhesive force by CFE. They obtained a power law dependence of the interfacial mean force on R over the range of variation in particle size, R = 2 ~ 10 μm, and Q_0/m constant. They found that the mean force increases with the power of R from 2.2 to 2.4. They also showed that the mean force of the toner for R = 5 μm and Q_0/m = 16 μC/g is about 100 ~ 200 nN. Accordingly, the power dependence on R evaluated for $E'(R) = 0$ in Fig. 7 agrees well that for CFE.[10] We infer that the dilute toner density of $E'(R) = 0$ is commonly used in CFE, in order to detect optically the number of toner particles before and after the action of centrifugal force.[9,10] Although the actual experimental situation for CFE will be governed by the distribution of Q_0/m, R, the shape of toner particle, and the packing ratio P, the condition $E'(R) \cong 0$ should be an adequate approximation for conventional CFE.

A detachment field for intimate contact toner particles has been measured under conditions of PEE.[5] PEE measures the number of toner particles that are detached from one electrode and collected by the other one, and the detachment electric field is defined as that obtained when detachment reaches 50%. This experiment is similar to measurement of the electric field corresponding to $\eta = 0.5$ for ETP. However, in PEE, the density of toner particles on the photoreceptor is enough low, and there is an air gap between the electrodes in order to confirm detachment of the toner particles.[11,12] Although the detachment of small particles requires a large threshold detachment field in PEE, as shown in Table II, the impossibility of detachment of small toner particle is not expected for PEE, because the toner charge is constant in an electric field where $dE/dz = 0$, by Maxwell's equation. The non-electrostatic interfacial force, KR, has not been accounted for in evaluation of the detachment forces in previous studies of PEE.[5,11–14] We suggest that the large difference in forces between CFE and PEE results from this term.

Discussion and Conclusion

The interfacial force between the intimate contact toner particle and the photoreceptor in ETP is schematically summarized in Fig. 8, and the three problems mentioned in the Introduction are explained with this figure. The maximum force, $Fmax$, and the threshold detachment field, $E_-(R)$, are obtained from Table II. $Fmax$ and $E_-(R)$ shift to a lower value and to a more negative value with decreasing R, respectively. When the transfer voltage Vt ($\propto \eta_0$) is increased with constant R, the variation in $E_-(R)$ becomes magnified relative to that in the applied field, $E'(R)$, as shown in Fig. 4, and then transfer efficiency η shows a peak at the mean Vt of the detachment range of η_0.[2] The relative relationship between $E_-(R)$ and $E'(R)$ explains the impossibility of detachment of small toner particles during ETP as shown in Figs. 5 and 6. These particles are observed as residual toner on the photoreceptor after ETP.[3,4] The resultant detachment force in a CFE increases with $R^{2.2}$ when Q_0/m is constant, as shown in Fig. 7, and this dependence has been previously observed in CFE.[10] The mirror image force dominates CFE for R > 6.4 μm in the present evaluation. In ETP and PEE, small toner particles require large negative $E_-(R)$ compared to large toner particles, indicating the opposite particle size dependence to the detachment force in CFE, as shown in Figs. 7 and 8.

This study assumes div $E_2 \neq 0$ for the electric field, E_2, of the toner layer in Eq. (6). Accordingly, the variation of the toner charge density occurs on application of Vt, and is governed by the arbitrary parameter λ, which is called the influence factor for the charge density. When $\lambda = 0$, the toner charge remains constant and the first and second problems are not resolved. The state div $E_2 \neq 0$ also gives rise to dipole and quadrupole induced moments in a spherical toner particle. This treatment is different from that of Hays and coworkers[5,11] who proposed localized charge patch regions on irregular shaped toner particles[12,13] and a dumbbell type charge distribution on the spherical toner particle[14] to explain the third problem. Such phenomena may occur experimentally in a complex toner ensemble. However, it is found even that without these assumptions, the three problems can be explained using minimum non-electrostatic interfacial force KR, and analysis of the dynamic state, as shown in Figs. 2 and 8.

One of next problems is experimental observation of the variation in toner charge with application of external transfer voltage. Hays[16] used variation of the toner charge to explain background toner in the development process. However, such variation in the toner charge distribution has not been confirmed.[17] The variation of toner charge may be reversible over a short time scale and may also show a weak hysteresis for change in Vt. The toner charge influence factor, λ, is thus also important for electrophotography; the cause of λ is obscure, and may relate to toner triboelectric properties, which depend, in turn, on the ingredients, particle size, and shape of the toner particle. Another issue is the cause of the non-electrostatic interfacial force KR; the present value of the coefficient, K, corresponds to the value given by the dispersion theory of the van der Waals force.[3] However, deformation of the contact area of the toner particle on the photoreceptor[3,13,15] has been proposed as an alternative mechanism for the force. Such deformation may enhance the interfacial non-electrostatic force more than expected from the dispersion theory. The interfacial adhesive force is significant not only in electrophotography, but also in many technical areas requiring handling of particles in the size regime of several micrometers. Therefore, well-controlled experiments related to the distributions of toner charge, radius, shape, packing ratio, electric permittivity, and time constant, as well as to the preparation time for the experiments will be required in future work.

Appendix:

Final form of Eq. (17) is given by the next equation, where $f(n) = 1/[2(1+\chi)]^{2n}$.

$$F = QE\,\{1 + b/2 + (c/8)\Sigma[f(n)g(n)(n+1)(2n+3)]\} -$$
$$[\,Q^2/16\pi\varepsilon_0 R^2(1+\chi)^2]\{1 + d\Sigma\,[f(n)g(n)(n+1)]\}$$
$$-[\pi\varepsilon_0 R^2E^2][cg(1)/2]\,\{3 + (d/2)\Sigma\,[f(n)g(n)(n+1)^2(n+2)]\}$$
$$+ (3P/\kappa)QE\,\{\,a + (ab/4)\; + (3be/8) + (c/16)\Sigma[f(n)g(n)$$
$$(n+1)^2][a + (e/16)(n+2)(5n+13)]\}$$
$$-(3P/\kappa)[Q^2/16\pi\varepsilon_0 R^2(1+\chi)^2]\{a + (3e/4) +$$
$$(d/2)\Sigma[f(n)g(n)(n+1)][a + (e/16)(n+2)(5n+11)]$$
$$+ (3P/\kappa)(e/8)\mathbf{[}3a + (15e/4) + (d/4)\Sigma[f(n)g(n)(n+1)^2$$
$$(n+2)][a + (3e/16)(n+2)(n+3)]\mathbf{]}\}$$

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