Effect of Charge Transfer on Electrostatic Adhesive Force under Different Conditions of Particle Charge and External Electric Field

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Abstract

The electrostatics of charged particles are utilized for various applications. This paper presents an analysis of the electric field and electrostatic adhesive force on a charged dielectric particle lying on a conducting plane under an externally applied electric field. The purpose of the analysis is to quantitatively investigate the force variation when there is charge transfer between the particle and the conducting plane. We treat the distribution of charges as either uniform on the particle or partially on the lower half. The transferred charge density is assumed to be dependent on the applied electric field. The results show that the electric field is very strong near the contact point, where the charge transfer may occur. Without the charge transfer, the electrostatic adhesive force on a negatively charged particle increases when the applied field is in the upward direction from the plane. However, in the presence of charge transfer, the force may vary only slightly with the applied field or even show a reverse tendency if the transfer charge density depends significantly on the applied field.

Keywords: electric field, charged particle, electrostatic force, charge transfer, numerical field calculation

1 Introduction

The electrostatics of particles are used in a variety of powder-related industry applications, such as electrostatic precipitators, painting, coating and separation [1]. In many cases, particles are charged and their movement is controlled by inserting an electric field. We sometimes need to transfer charged particles from one surface to another. For example, toner particles are detached from a photoconductor to a transfer belt or to a paper in electrophotography [2]. On the other hand, re-entrainment of particles is regarded as a problematic issue in electrostatic precipitation [3]. The detachment of charged particles from a substrate involves the Coulomb force inserted by an electric field [4, 5], the electrical image force between the particle charges and their images with respect to the substrate [6-8] and other surface forces, such as the van der Waals force [9, 10]. For electrostatic applications related to particle manipulation such as the transfer of toner particles, the electrostatic force is predominant over the van der Waals force and the effect of the liquid bridge force is usually small by a hydrophobic treatment of particle surface.

Typically, charges are introduced on particles by triboelectricity [11-14], induction charging [15, 16] or corona discharge [17-19]. For dielectric particles, the condition of the equipotential does not hold on the particle surface. For this reason, the particles may have various forms of charge distribution on the surface, depending on the charging method and the amount of particle charges [20]. The charge distribution has an effect on the behavior of the electrostatic force acting on the particles. The electrostatic adhesion does not take place directly at the contact surface, but is a result from the long-range electrostatic image force acting on particle charge, which attracts a charged particle to the substrate. The electrostatic adhesive force increases remarkably if charges are nonuniformly concentrated near the contact point between a particle and a substrate [5, 21, 22]. Nonuniform charging can cause significant discrepancy between the measured adhesive force and the estimated one based on the point-charge model. The behavior of electrical force on a charged particle when subjected to an applied electric field also varies with the charge distribution on particle surface [5, 21, 23, 24].

Electrostatic adhesive force was recently investigated using air flow to detach dielectric particles from a conducting plane under an electric field where the particles were charged by tribocharging [25]. The results showed that the particles, which were negatively charged, exhibited a consistent increase in adhesion with increasing electric field in the downward direction. The opposite tendency was observed when the field was in the upward direction. These results contradict typical expectations because a downward electric field tends to lift a negatively charged particle from the substrate, thus reducing the adhesion. The effect of charge transfer between the particle and the conductor was suggested to be a possible cause of the aforementioned variation of the electrostatic adhesion in the experiments.

In this paper, we present an analysis of the electrostatic adhesive force between a charged dielectric particle and a conducting plane under an externally applied electric field. The charge is distributed either uniformly over the entire particle surface or partially on the lower half of the particle. A field-dependent charge transfer is assumed to occur on the particle surface near the conducting plane. The charge transfer may arise from the contact between different materials, as described in [12, 26, 27]. Nonlinear volume or surface resistivity of particle may also cause charge leakage. We apply a numerical field calculation to obtain the variation of the electrostatic force. The main objective of this work is to quantitatively study the effects of the charge transfer on the electrostatic adhesion under different conditions of particle charges and external field magnitudes.

2 Configuration of Analysis

Figure 1 shows the configuration used for the analysis in this work. A charged dielectric particle of radius R lies on a grounded conducting plane under a uniform electric field $\mathbf{E}_{ext}$. The electric field is taken to be positive in the upward direction. We assume the dielectric constant ε_r = 3 for the particle and ε_r = 1 for the surrounding medium (air).

We consider two types of charge distribution on the particle before charge transfer occurs. Surface charge density σ is equal to σ_0 and is uniform over the particle surface for the first type. For the second kind, the charge density is zero on the upper half and constant ($\sigma = \sigma_0$) on the lower half of the particle surface, that is, the particle is partially charged in the latter case.

The change of the surface charge density due to charge transfer between the particle and the conducting plane is taken into account by designating Patch A that occupies $0 \leq \theta \leq \alpha$, where θ is the zenith angle measured from the contact point (See Fig. 1.). We assume that the charge density σ_A on Patch A follows a relationship

$$\sigma_A = \sigma_0 + \sigma_{E0} + k_E E_{ext} \tag{1}$$

where σ_{E0} is the transferred charge density in the absence of the externally applied electric field E_{ext} and k_E is a coefficient representing the effect of the field E_{ext} on the charge transfer. This concept results from the previous studies [26, 28, 29].

In the calculation, the particle radius R is equal to 2.5 μm. We consider the original charge density σ_0 = −10, −20 and −30 μC/m^2. The applied field E_{ext} is between −3 and 3 kV/c m. These values are based on the recently reported experiment [25], where corrections are needed. That is, the actual unit of electric field is kV/m (not V/m) for Figs. 11 and 13 in [25]. The patch angle α = 15°. For the charge transfer, we use σ_{E0} values between −10 and −30 μC/m^2 and k_E equal to 10, 20 or 30 (μC/m^2)(kV/cm)$^{-1}$.

The model of charge transfer in the current work assumes a change in particle charge near the contact point, which is not limited to a specific physical mechanism of charge transfer. For example, in the case of negatively charged toner particles, the contact point of the particle has a negative charge caused by the charge transfer. The parameters in Eq. (1) basically depend on the material properties such as work function, surface conductivity, and the energy states of charges. In addition, the patch angle α also depends on several factors such as particle geometry, field distribution, and the surface conductivity. However, it is still difficult to accurately estimate the values of σ_{E0} and k_E. In this work, we try to investigate how the values can affect the electrostatic force under the application of external electric field. First, we assume that the dielectric particle acquires negative charge by contacting with conducting plane; thus, the value of σ_{E0} arising from charge transfer is negative. The positive field in the upward direction should hinder the transfer of negative charge from the plane to the particle, and positive k_E is then chosen here. The surface charge density is supposed to be the order of 10^2 μC/m^2 taking into account gas discharge of fine particles with surface roughness. In this condition, the absolute values of σ_{E0} and k_E are tentatively assigned to the model.

Particle deformation can occur when a particle makes a contact with a substrate. The deformation has an effect on the contact area, and hence the charge transfer. However, under the application of strong electric field, the electric field alters significantly near the contact point. We expect that the influence of the electric field takes place on a wider area than the contact area, and the charge distribution based on the surface conductivity is more significant. Therefore, the contribution from the deformation may be negligible in this study.

3 Calculation Method

We apply the boundary element method [30], which is a numerical field calculation method, to determine the electric field distribution in the configuration of Fig. 1. The method is based on an integral relationship between the potential ϕ and the normal component E_n of the electric field on the boundary of a domain. For potential ϕ_i at point i in domain Ω enclosed by boundary Γ,

$$C_i\phi_i = \int_\Gamma \psi(\mathbf{r},\mathbf{r}_\Gamma)E_n \,\mathrm{d}\Gamma + \int_\Gamma \frac{\partial\psi(\mathbf{r},\mathbf{r}_\Gamma)}{\partial n}\phi \,\mathrm{d}\Gamma \tag{2}$$

In the equation, **r** is the position of i, $\mathbf{r}_\Gamma$ is the position on boundary Γ, ψ is the fundamental solution, and C_i is a constant. For a smooth boundary Γ, $C_i = 1/2$ if i is on Γ and $C_i = 1$ if i is in Ω but not on Γ. For the configuration and the charging condition considered in this work, the potential is axisymmetric about the z axis in Fig. 1. The calculation is carried out using the axisymmetric coordinates shown in the figure. That is, **r** is defined by (ρ, z) coordinates and $\mathbf{r}_\Gamma$ by (ρ_Γ, z_Γ). Note that E_n is taken to be positive in the direction outward from Ω. The fundamental solution is expressed as

$$\psi(\mathbf{r},\mathbf{r}_\Gamma) = \frac{K\left(\sqrt{2n/(m+n)}\right)}{\sqrt{m+n}} \tag{3}$$

where K is the complete elliptic integral of the first kind, and

$$m = \rho^2 + \rho_\Gamma^2 + (z - z_\Gamma)^2 \tag{4}$$

$$n = 2\rho\rho_\Gamma \tag{5}$$

For the interior of the particle, Eq. (2) becomes

$$C_i\phi_i = \int_S \psi(\mathbf{r},\mathbf{r}_\Gamma)E_n^I \,\mathrm{d}\Gamma + \int_S \frac{\partial\psi(\mathbf{r},\mathbf{r}_\Gamma)}{\partial n}\phi \,\mathrm{d}\Gamma \tag{6}$$

where S is the particle surface, and the superscript I denotes the field component inside the particle. For the exterior of the particle, we take the normal component E_n^E in the same direction as E_n^I and modify Eq. (2) to include the contribution of $\mathbf{E}_{ext}$ as

$$C_i\phi_i = -\int_S \psi(\mathbf{r},\mathbf{r}_\Gamma)E_n^E \,\mathrm{d}\Gamma + \int_S \frac{\partial\psi(\mathbf{r},\mathbf{r}_\Gamma)}{\partial n}\phi \,\mathrm{d}\Gamma - \mathbf{E}_{ext}\cdot(\mathbf{r}-\mathbf{r}_0) \tag{7}$$

The superscript E denotes the normal field component on S in the exterior of the particle, and $\mathbf{r}_0$ is the position of the reference potential. The relationship between the normal electric field on both sides of the particle surface S can be written as

$$\varepsilon_0\left(E_n^E - \varepsilon_r E_n^I\right) = \sigma \tag{8}$$

For the boundary element method, the contour of the particle is discretized into elements. The potential ϕ and normal electric field E_n are interpolated as a function of the corresponding nodal values on each element. The existence of the conducting plane and the induced charges on the plane is taken into account by using image elements of the particle surface below the conducting plane to fulfill the condition of constant potential. Eqs. (6)–(8) are applied to each node position to construct a linear equation system, which is solved for the nodal ϕ and E_n values on the particle. An in-house program is used for the calculation. Approximately 1440 second-order curved elements are utilized for the particle contour to attain high accuracy of the calculation results. After obtaining the field solution, we determine the electrostatic force **F** acting on the particle by integrating the Maxwell stress over particle surface S,

$$\mathbf{F} = \varepsilon_0\int_S \mathbf{E}E_n^E - \frac{1}{2}E^2\mathbf{n}\,\mathrm{d}s \tag{9}$$

where **n** is the unit normal vector on S. The electric fields are taken from the exterior side for the integration.

4 Results and Discussion

4.1 Uniformly Charged Particle without Charge Transfer

Fig. 2 shows the distribution of the normal component E_n of the electric field (in the exterior) on the surface of a uniformly charged particle when the applied field does not exist. The angle θ is measured from the contact point. The electric field is very strong near the contact point where θ = 0°. The calculated electric field is significantly higher than the typical dielectric strength of air. However, the field decreases rapidly with distance from the particle and cannot induce electrical discharge by the streamer mechanism. However, such a strong electric field in Fig. 2 may lead to the transfer of charge between the particle and the conducting plane, which are very close to each other near the contact point.

Insertion of an external field $\mathbf{E}_{ext}$ may increase or decrease the electric field distribution near the contact point. Fig. 3 shows the variation of the normal electric field E_n with applied field $\mathbf{E}_{ext}$ for a particle uniformly charged to σ = −10 μC/m^2. A positive electric field (i.e., in the upward direction) intensifies the electric field near the contact point but mitigates the field on the upper half of the particle. A negative field value has the opposite effect on the field distribution.

Figs. 4(a) and 4(b) show the distribution of the tangential electric field E_t on the particle surface for a uniformly charged particle with σ_0 = −10 and −30 μC/m^2, respectively. A positive tangential field is defined in the direction of increasing θ , i.e., away from the contact point. We can see from the figure that E_t is strongly positive near the contact point with the peak located around θ = 15°. On this area, the Coulomb force due to positive E_t acts on a negative charge in the $-\theta$ direction. Therefore, E_t tends to move the particle charges to the vicinity of the contact point. The tangential field and the force due to E_t are enhanced by the application of positive E_{ext}.

Comparison between Fig. 3 and Fig. 4(a) shows that the magnitudes of the tangential field are much smaller than those of the normal electric field. We may consider the roles of the normal and tangential field components as follows. The normal field E_n makes a major contribution to the transfer of charge between the particle and the plane, whereas the tangential field indirectly assists the charge transfer by moving charges along the particle surface to the vicinity of the contact point. The movement of charges along a surface may require a lower electric field than that required for a direct detachment of charges from the surface.

Fig. 5 shows the electrostatic adhesive force F_a, the downward component of **F**, on uniformly charged particles with different charge density σ_0 as a function of the applied field E_{ext}. The electrostatic force becomes stronger with increasing field magnitude in the upward direction. The contribution of E_{ext} to F_a can be considered from the Coulomb force acting on the surface charges for the range of E_{ext} in this figure because negative charges on the particle are attracted to the plane by an upward electric field. The F_a-E_{ext} relationships are approximately linear for the considered σ_0 and E_{ext} values.

4.2 Partially Charged Particle without Charge Transfer

Fig. 6 shows the distribution of E_n as a function of θ on a particle partially charged from θ = 0 to 90° in the absence of an applied field. The field distribution is similar to that in Fig. 2 on the lower half, but the field is very small on the upper half due to the absence of surface charge. For the same σ_0 value, the total charge amount on the partially charged particle is equal to half of that on the uniform charge.

Therefore, Fig. 6 and Fig. 2 imply that the electric field will be stronger in the case of partial charging if the total charge amounts are the same.

The effects of the external field $\mathbf{E}_{ext}$ on the normal electric field for the partially charged particle are not shown here, but they are similar to those for the uniformly charged particle. Fig. 7 shows the variation of the tangential field E_t on the partially charged particle. On most of the charged area, E_t still acts to move negative charges along the surface to the contact point. Near the edge of the charged area, the negative E_t repulses charges to the upper half. An application of positive (upward) E_{ext} increases the field value and reduces the area of negative E_t.

Fig. 8 shows the variation of the adhesive force F_a with the magnitude E_{ext} of the externally applied electric field on the partially charged particle. The force behavior is similar to that in Fig. 5 for the uniformly charged particle, that is, the adhesion increases with increasing upward electric field E_{ext}, and the F_a-E_{ext} relationships are approximately linear for the considered ranges of σ_0 and E_{ext}. The electrostatic force varies linearly with the square of the electric field on the particle surface. Therefore, the adhesion is usually stronger on a partially charged particle than on a uniformly charged particle for the same total amount of charge and applied electric field. For example, in the absence of E_{ext}, F_a magnitude is 0.61 nN on the partially charged particle with $\sigma_0 = -20$ μC/m^2, higher than 0.35 nN on the uniformly charged particle with $\sigma_0 = -10$ μC/m^2.

4.3 Force Variation due to Charge Transfer

The aforementioned results show that both uniform and partial charge distributions exhibit an increase of electrostatic adhesion when applying an upward electric field, and vice versa. The adhesive force behavior varies linearly with the applied field for the considered ranges of σ_0 and E_{ext}. This section investigates the variation of the adhesive force behavior when there are charges transferred between the particle and the conducting plane. We consider that the charge transfer is dependent on the applied electric field E_{ext}, as given in Eq. (1). We assume a patch angle $\alpha = 15°$, which is approximately the angle of the peak tangential field before charge transfer occurs.

Figs. 9(a) and 9(b) show the calculation results of the uniformly charged particle when $\sigma_{E0} = -10$ and -30 μC/m^2, respectively, and $k_E = 20$ (μC/m^2) (kV/cm)$^{-1}$. The F_a-E_{ext} characteristics are given on each graph for three values of the original charge density σ_0. Fig. 9 shows that the behavior of F_a changes significantly from that in Fig. 5 for the uniformly charged particle. The adhesive force increases or decreases only slightly with the change in the applied electric field E_{ext}. Although the force magnitudes depend on the original charge density σ_0, the F_a-E_{ext} characteristics are similar for the same σ_{E0} and k_E values. A comparison between Figs. 9(a) and 9(b) shows that the larger σ_{E0} value results in stronger adhesive force. However, the effect of σ_{E0} is small for positive E_{ext} values.

Fig. 10 shows the variation of F_a with E_{ext} on the uniformly charged particle when $\sigma_{E0} = -30$ μC/m^2 and $k_E = 10$ or 30 (μC/m^2) (kV/cm)$^{-1}$ are used as the charge transfer parameters. For the smaller k_E value in Fig. 10(a), the particle exhibits an increase of adhesive force with increasing applied field E_{ext}. The F_a-E_{ext} characteristics in the figure are similar to the corresponding cases without charge transfer shown in Fig. 5.

With the higher k_E value, the adhesive force in Fig. 10(b) is weakened with increasing electric field. From $E_{ext} = -3$ kV/cm, the decrease of the adhesive force is moderate but consistent. The force reaches its minimum at an E_{ext} value between 2 and 3 kV/cm. We may observe the roles of the charge transfer from the change in the normal electric field E_n, which makes a major contribution to the electrostatic force (as E_n is much larger than E_t). Fig. 11 illustrates the variation of E_n on the particle with E_{ext} corresponding to the cases in Fig. 10(b), i.e., $\sigma_{E0} = -10$ μC/m^2, $\sigma_{E0} = -30$ μC/m^2 and $k_E = 30$ (μC/m^2)

(kV/cm) $^{-1}$. It is clear that the charge transfer reduces E_n near the contact point with increasing E_{ext} from −1 to 1 kV/cm. The change of E_n with E_{ext} shows an opposite tendency in comparison with that in Fig. 3. The reduction of E_n weakens the electrostatic attractive force on the particle.

Note that the external field induces polarization in the dielectric particle. The interaction between the polarization charge and its image on the conducting plane yields an increase in the attractive electrostatic force. The effect of polarization becomes more important with increasing the external electric field. As a result, a further increase of E_{ext} higher than 2–3 kV/cm results in stronger adhesive force in Fig. 10(b) due to the predominant attractive force on the polarization charge [31].

Figs. 12 and 13 show the variation of the adhesive force on the partially charged particle when charge transfer occurs. For k_E = 20 (μC/m^2) (kV/cm) $^{-1}$, the adhesive force in Fig. 12 is reduced by increasing the electric field for both values of σ_{E0}. The change in σ_{E0} has a more prominent effect on the adhesive force under a strong negative field than under a positive field. Comparing Fig. 12 with Fig. 9, we can see that the contribution of the charge transfer is more clearly seen on the partially charged particle.

Fig. 13 shows the F_a-E_{ext} behavior for different k_E, which demonstrates that the k_E value significantly affects the behavior of F_a. For the partially charged particle having σ_0 between −10 and −30 μC/m^2, the force minimally varies with the electric field when the smaller k_E value is used in Fig. 13(a). On the other hand, with the larger k_E value, there is a clear reduction of the adhesive force with increasing applied electric field. The adhesive force reaches its minimum when E_{ext} is approximately 2–3 kV/cm, similar to the cases of the uniformly charged particle.

In summary, our calculation results in this work demonstrate that charge transfer between the particle and the plane may have a significant role in the electrostatic adhesion of the particle if the parameter k_E, representing the dependency on the electric field, is sufficiently large. For the same σ_0, σ_{E0} and k_E values, the effect of charge transfer is more prominent on the partially charged particle than on the uniformly charged particle. If charge is distributed on a smaller area of the particle surface, the charge transfer is expected to have a greater role in the adhesion, which causes the reduction of electrostatic adhesion with increasing electric field in the experiments.

5 Conclusions

In this work, we analyzed the effects on the electrostatic adhesion of the charge transfer between a charged dielectric particle and a conducting plane. In the absence of charge transfer, the adhesion of a negatively charged particle becomes stronger with an application of external electric field upward from the plane. However, a change in the surface in a small area near a contact point mitigates the effect of the applied field or even reverses the tendency of the force variation with the applied field, that is, the electrostatic adhesion may be weakened by the upward electric field, provided the degree of the charge transfer varies significantly with the magnitude of the external field.

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Figure Captions

Fig. 1. Configuration of a charged dielectric particle under an externally applied field $\mathbf{E}_{ext}$.

Fig. 2. Distribution of the normal electric field on a uniformly charged particle in the absence of applied field $\mathbf{E}_{ext}$.

Fig. 3. Variation with the applied field $\mathbf{E}_{ext}$ of the normal electric-field distribution on a particle uniformly charged to −10 μC/m^2.

Fig. 4. Tangential electric field on a uniformly charged particle with σ_0 equal to (a) −10 and (b) −30 μC/m^2.

Fig. 5. Adhesive electrostatic force F_a as a function of E_{ext} on a uniformly charged particle for different σ_0 values.

Fig. 6. Distribution of the normal electric field on a partially charged particle in the absence of applied field $\mathbf{E}_{ext}$.

Fig. 7. Tangential electric field on a partially charged particle with σ_0 equal to (a) −10 and (b) −30 μC/m^2.

Fig. 8. Adhesive electrostatic force F_a as a function of E_{ext} on a partially charged particle for different σ_0 values.

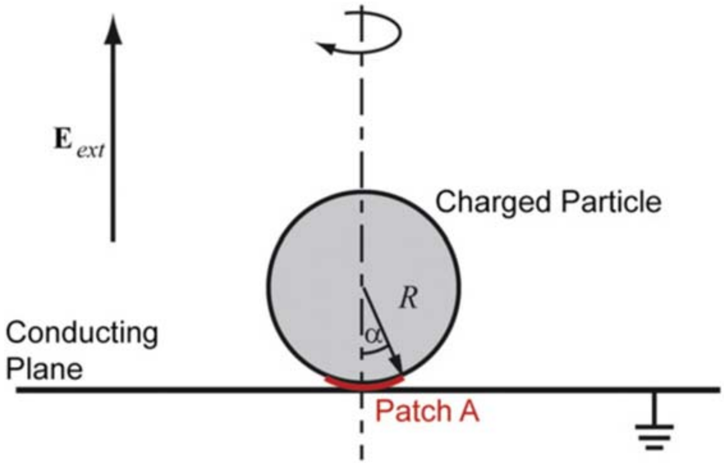
Fig. 9. Variation of F_a with E_{ext} on a uniformly charged particle in the presence of charge transfer with k_E = 20 (μC/m^2) (kV/cm)$^{-1}$ and σ_{E0} = (a) −10 and (b) −30 μC/m^2.

Fig. 10. Variation of F_a with E_{ext} on a uniformly charged particle with σ_{E0} = −30 μC/m^2 and k_E = (a) 10 or (b) 30 (μC/m^2) (kV/cm)$^{-1}$.

Fig. 11. Distribution of the normal electric field E_n for different E_{ext} in the case of uniform charging with σ_0 equal to −30 μC/m^2 and the charge transfer given by σ_{E0} = −30 μC/m^2 and k_E = 20 (μC/m^2) (kV/cm)$^{-1}$.

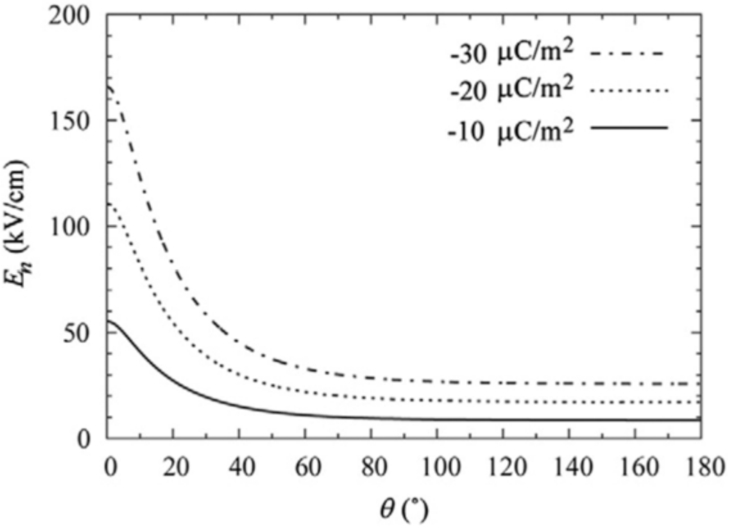
Fig. 12. Variation of F_a with E_{ext} on a partially charged particle with k_E = 20 (μC/m^2) (kV/cm)$^{-1}$ and σ_{E0} = (a) −10 and (b) −30 μC/m^2.

Fig. 13. Variation of F_a with E_{ext} on a partially charged particle with σ_{E0} = −30 μC/m^2 and k_E = (a) 10 or (b) 30 (μC/m^2) (kV/cm)$^{-1}$.



$\mathbf{E}_{ext}$
Charged Particle
R
α
Conducting
Plane
Patch A

Fig. 1



200
150
100
50
0
-30 μC/m2
-20 μC/m2
-10 μC/m2
E_n (kV/cm)
0
20
40
60
80
100
120
140
160
180
θ (°)

Fig. 2

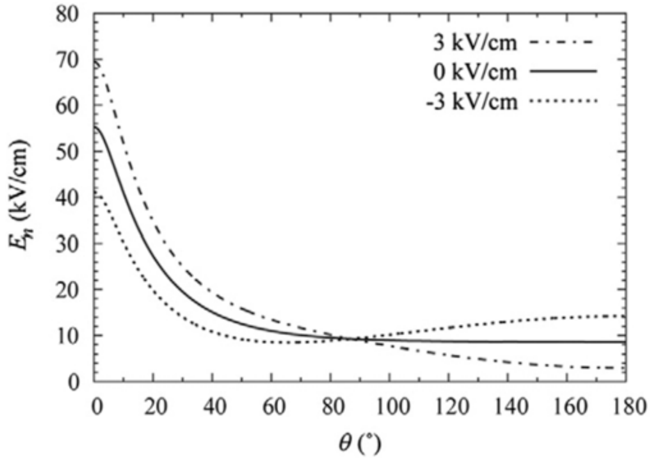

3 kV/cm
0 kV/cm
-3 kV/cm
E_n (kV/cm)
θ (°)

Fig. 3

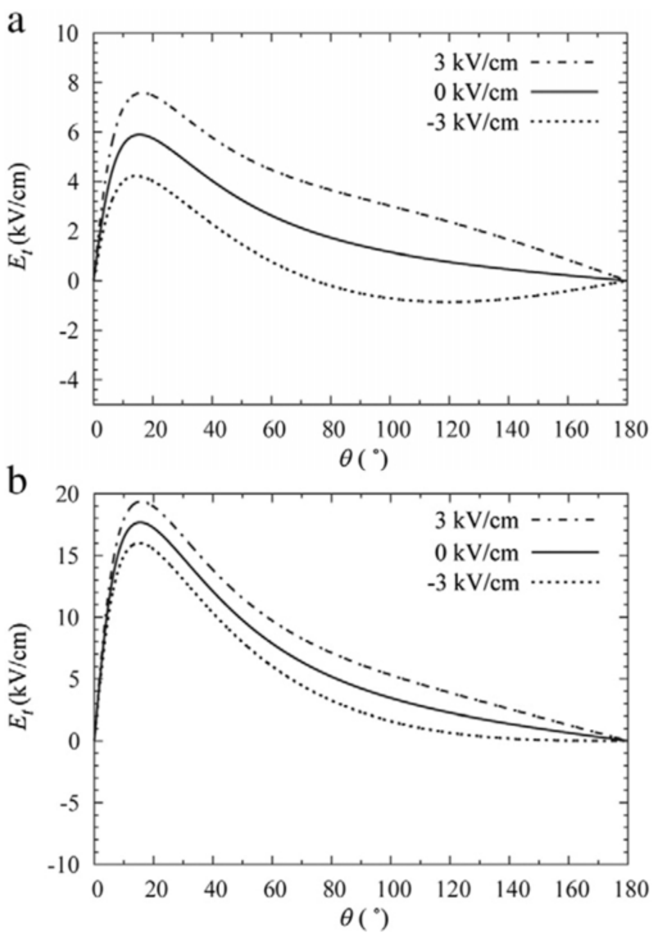

a
3 kV/cm
0 kV/cm
-3 kV/cm
E_t (kV/cm)
θ (°)
b
3 kV/cm
0 kV/cm
-3 kV/cm
E_t (kV/cm)
θ (°)

Fig. 4

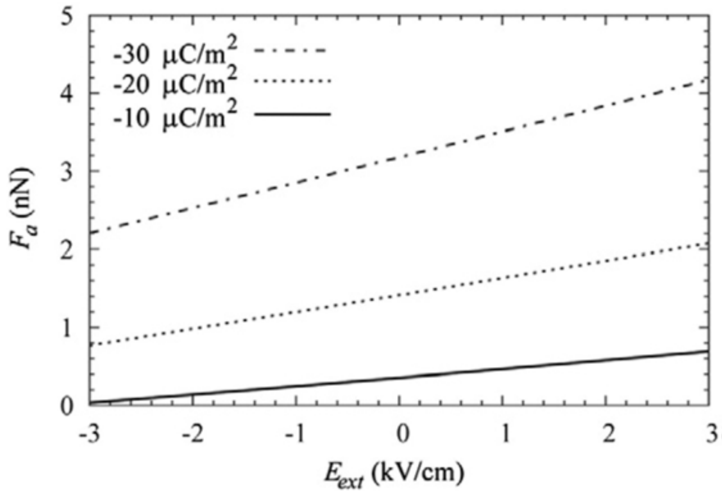


Fig. 5 σ_0

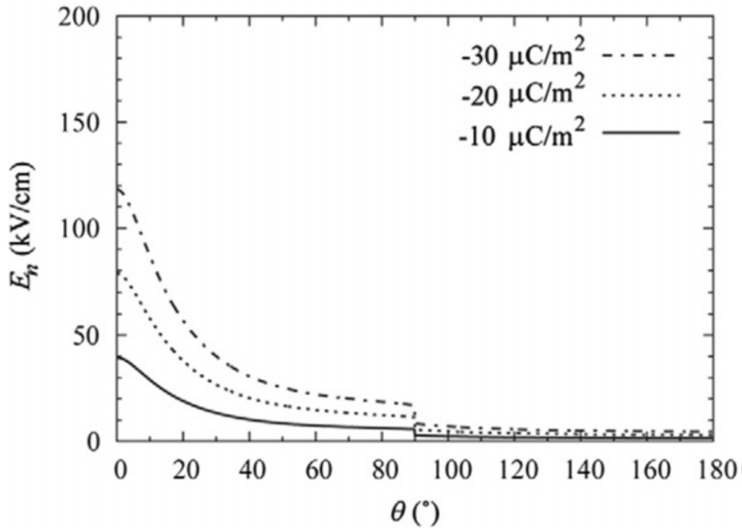


Fig. 6

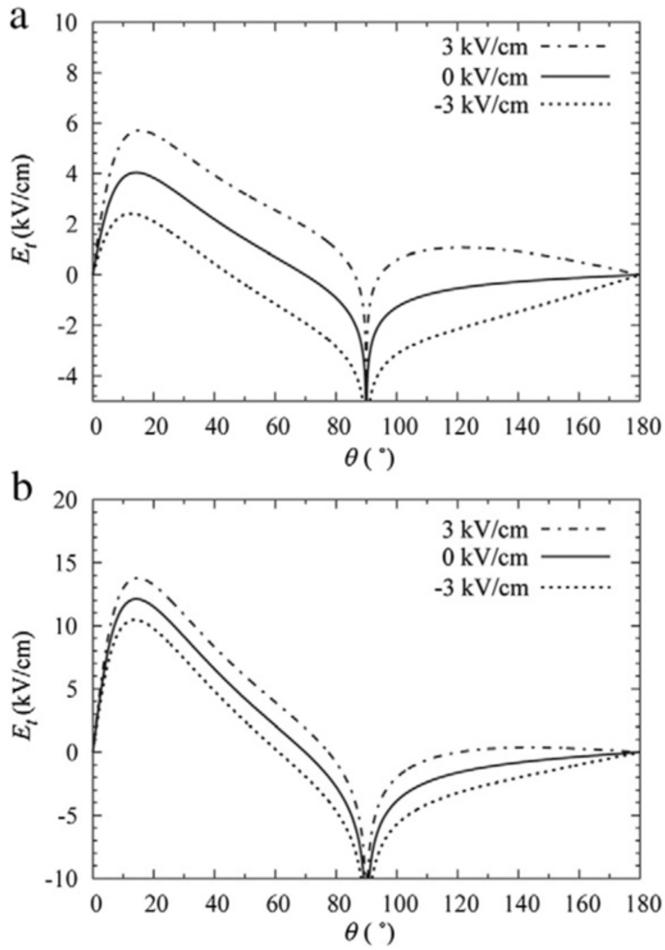


Fig. 7 0

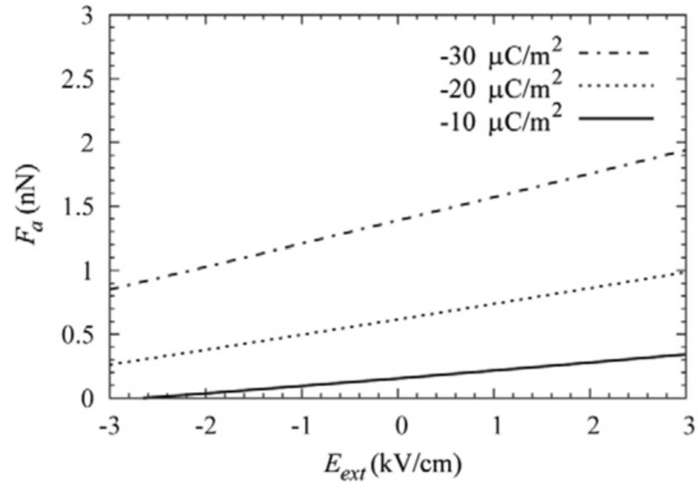


Fig. 8 σ_0

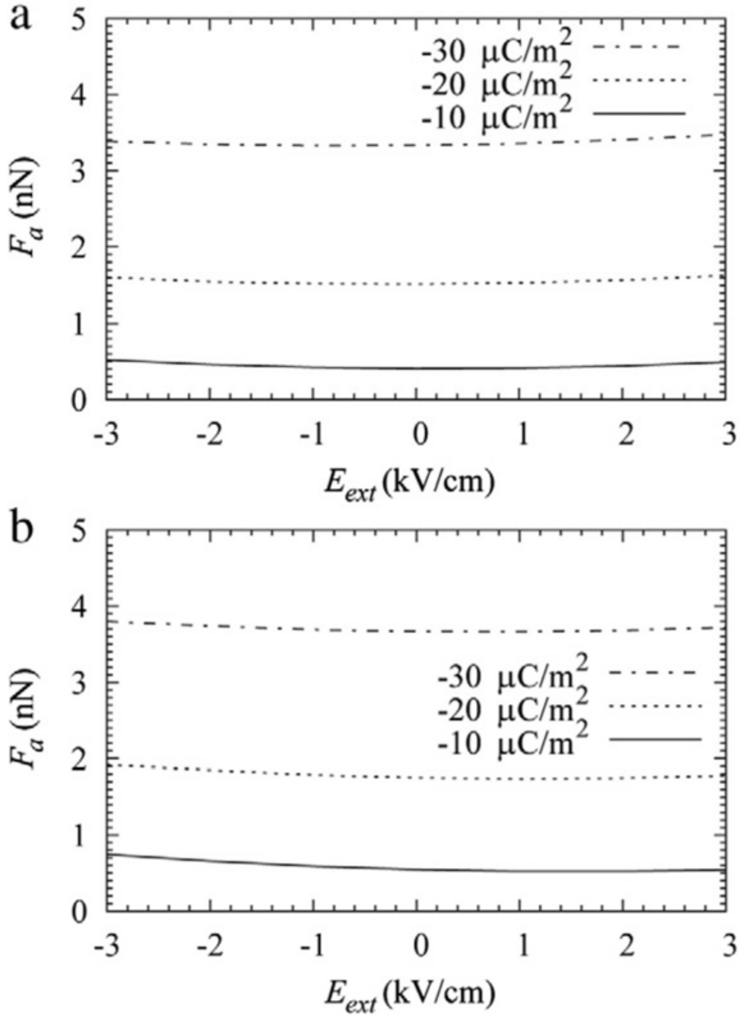


Fig. 9

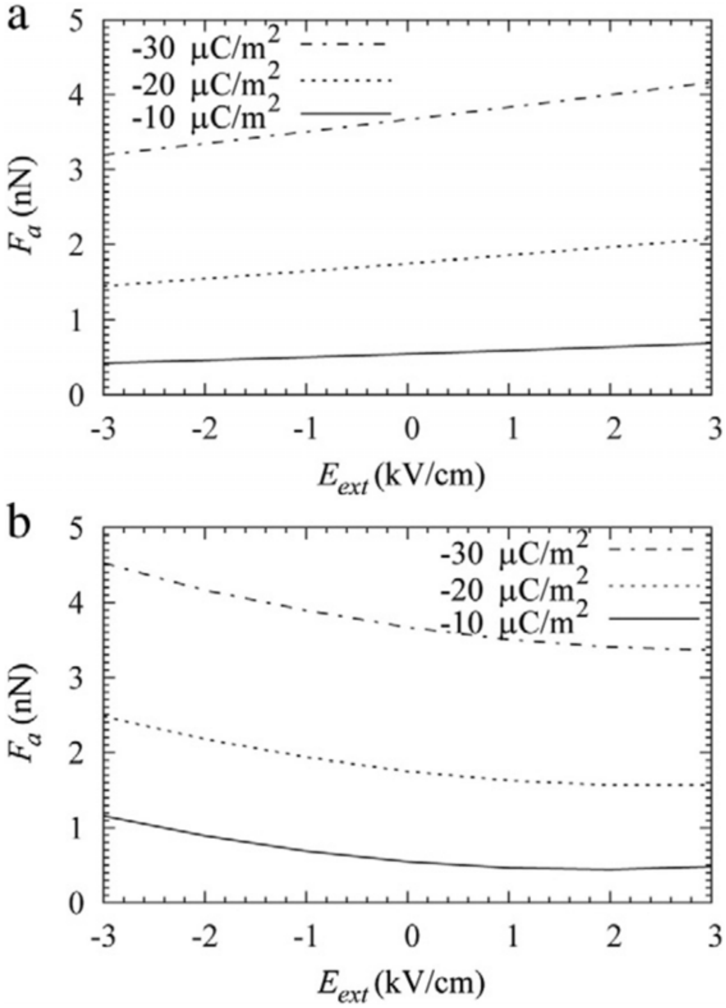
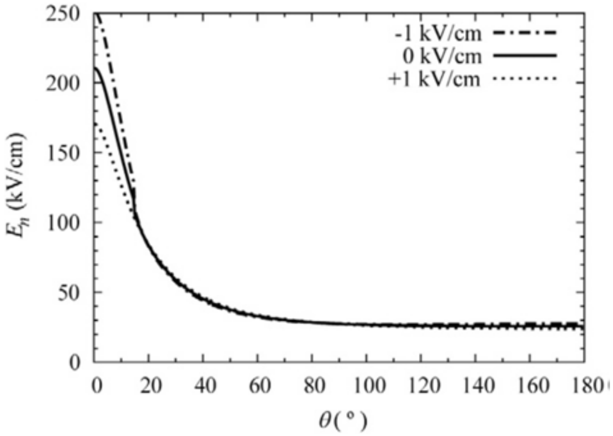

a
-30 μC/m2
-20 μC/m2
-10 μC/m2
F_a (nN)
E_ext (kV/cm)
b
-30 μC/m2
-20 μC/m2
-10 μC/m2
F_a (nN)
E_ext (kV/cm)

Fig. 10



(b)

Fig. 11

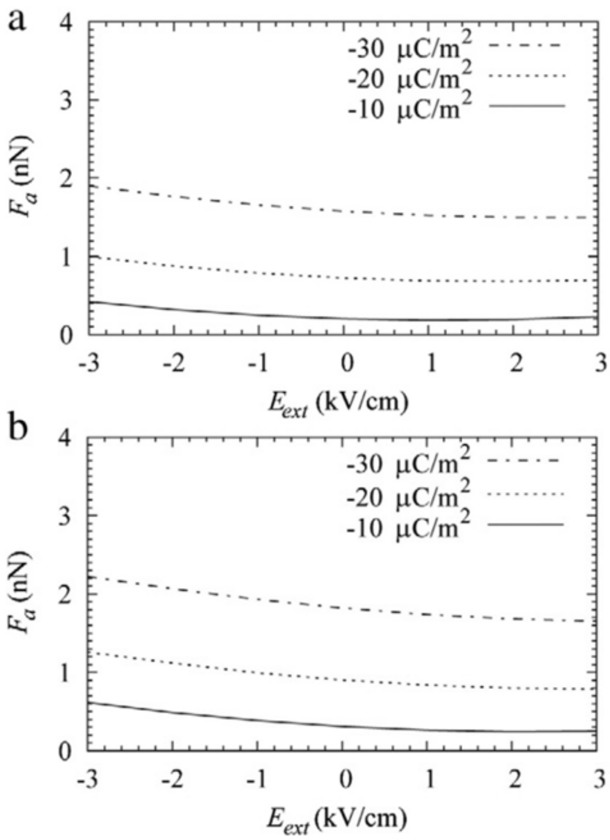


Fig. 12

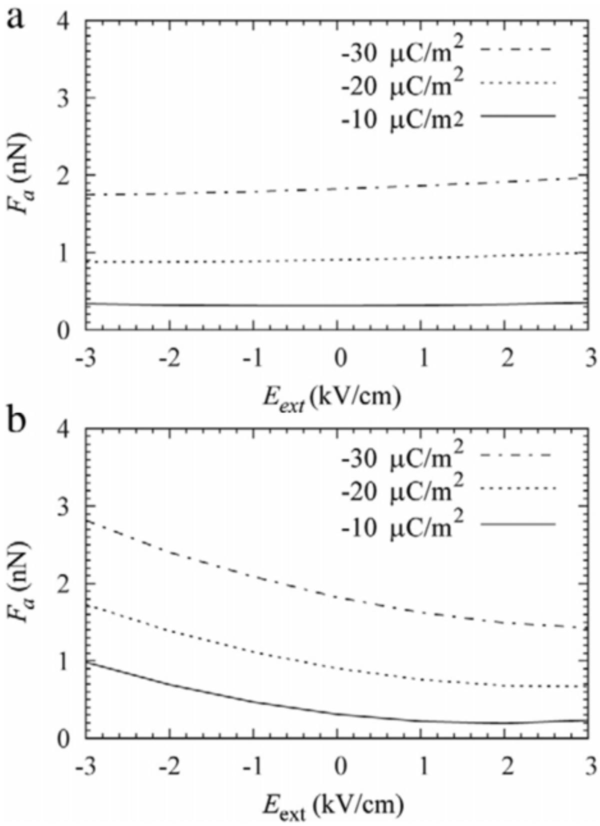

a
-30 μC/m2
-20 μC/m2
-10 μC/m2
F_a (nN)
E_ext (kV/cm)
b
-30 μC/m2
-20 μC/m2
-10 μC/m2
F_a (nN)
E_ext (kV/cm)

Fig. 13