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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.

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

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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

Fig. 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 $\varepsilon_r = 3$ for the particle and $\varepsilon_r = 1$ 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 $0 \le \theta \le \alpha$, 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 $\sigma_0 = -10, -20$ and -30 μC/m^2. The applied field E_{ext} is between -3 and 3 kV/cm. 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 $\alpha = 15°$. 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

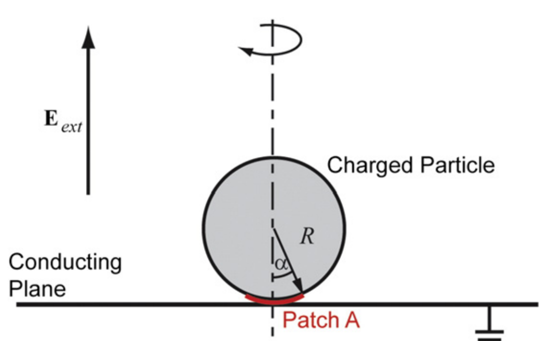

Fig. 1. Configuration of a charged dielectric particle under an externally applied field $\mathbf{E}_{ext}$.

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,

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

In the equation, $\mathbf{r}$ 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, $\mathbf{r}$ 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

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

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