

Theory of Electric Field Detachment of Charged Toner Particles

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Abstract

In the electrophotographic process, electric fields are used to detach and move charged toner particles from one surface to another. In principle, electric field detachment occurs when the applied electrostatic force overcomes the toner adhesion force to a surface. For triboelectrically charged toner, many measurements indicated that the electrostatic adhesion force of toner is much greater than that calculated for a uniformly-charged-dielectric-sphere model, suggesting that the surface charge distribution on a toner particle is nonuniform. In the present work, a triboelectric charging process is discussed for understanding the mechanism that causes a dumb-bell type charge distribution on toner particles, as previously found experimentally. The electrostatic force is computed for a dumb-bell type charge distribution on an isolated toner particle by means of a recently developed computational method using Galerkin finite-element technique. The effect of the relative spacing between electrodes on the electric field detachment of charged toner particles is examined in particular. The theoretical implication of electric field detachment of toner particles of different sizes is also discussed.

Introduction

Electrophotography (often also referred to as xerography), as invented by Chester Carlson in 1938[1], is essentially based on the physical fact that charged particles can be moved by an externally applied electric field. Toner particles used in electrophotography are typically about 10 μm in diameter and consist of a pigment dispersed in a polymer resin. These electrically insulating toner particles are usually charged by means of triboelectricity[1–5], as conveniently achieved in the two-component charging process. When brought into close proximity to an electrostatic latent image on a photoreceptor, the charged toner particles are expected to deposit on the photoreceptor according to the Coulomb force associated with the latent image to form a visible image. The developed image due to toner deposition on the photoreceptor is subsequently transferred to paper by an applied electric field to produce the printed document. The configurations for electric field detachment of toner in an electrophotographic system may vary considerably. For example, in some development systems, toner particles move across a relatively large gap between a toned donor surface and a receiver such as a photoreceptor. When toner is transferred from a photoreceptor to paper or an intermediate material, the toner particles typically provide a self-spacing between the donor and receiver to form a small-gap configuration. Yet the basic physical principles involved in electric field detachment of charged toner particles remain the same.

In view of its importance in electrophtography, the calculation of the electrostatic force on toner particles in contact with a material surface has been performed by many authors for various cases[6-10]. Most of those calculations were restricted to cases involving one sphere and one planar surface so as to make the problem tractable when using bispherical coordinates or multipole expansion methods. If the charge is assumed to be uniformly distributed on the dielectric sphere surface, the calculated electrostatic adhesion force on the sphere resting on a conductive plane is found to be much weaker than the measured values for triboelectrically charged toner[9-17]. This fact led to the concept of nonuniform charge distribution on triboelectrically charged toner particle surface[15] and subsequent investigations[9,10,16,17,19]. Many experimental results seem to be consistent with the assumption of a dumb-bell type charge distribution on toner particles.

In the present work, we first discuss the physical mechanism for a dumb-bell type charge distribution to form on a triboelectrically charged toner particle. Then, we compute the electrostatic force for the dumb-bell charge distribution on an isolated dielectric sphere by means of a recently developed computational method using a Galerkin finite-element technique[18, 19]. The effect of the relative spacing between electrodes on the electric field detachment of charged toner particles is examined in particular. We also discuss the theoretical implication of electric field detachment of toner particles of different sizes.

Tendency for a Dumb-Bell Type Charge Distribution to Form on a Triboelectrically Charged Particle

From a physical point of view, triboelectric charging (sometimes also called contact charging) occurs when two dissimilar material surfaces are brought into intimate contact. In a two-component charging process, the toner particles are typically mixed with much larger particles with different surface material properties. During the charging process, the granular mixture of toner and so-called carrier beads undergoes vigorous small-scale relative motions so that all the toner particles have an opportunity to be in contact with the carrier beads to acquire charge. When an electrically neutral toner particle first touches a carrier bead, only a small area on its surface where the intimate contact occurs can get charged. With a small area charged, however, the toner particle in random motion among the two-component mixture would statistically tend to have the same charged area contact with a carrier bead again, as driven by the mechanism of minimizing electrostatic energy. Therefore, a toner particle on a carrier bead surface is very likely to have a heavily charged area in contact with a carrier bead, as mentioned by Hays[10].

When another carrier bead comes in random motion near a toner particle that is already attached to a carrier bead at a heavily charged site, it can only contact the area on the toner particle opposite to that heavily charged site, because of the geometric constraints. Hence, the most likely statistical outcome is that the triboelectrically charged toner particles have a dumb-bell type nonuniform charge distribution on their surfaces as evidenced by experimental results[9, 10, 16].

Electrostatic Force on a Charged Spherical Particle

It is well known that the toner commonly used in electrophotographic machines consists of particles that are irregular in shape, because the particles are typically formed by a grinding process. The difficulty in theoretical description of toner adhesion arises from selecting a representative shape for irregularly-shaped toner particles. Although selecting any particular shape may suffer from criticisms as not exactly describing a realistic toner particle, the spherical shape is the most commonly used one in theoretical analyses. Not only does a spherical particle become amenable to mathematical solutions by various methods, but it also makes sense from a statistical point of view when simple averaging is performed over a large number of irregularly-shaped particles.

The problem considered here consists of a dielectric toner particle of spherical shape with radius R and net charge Q resting on an electrode of a parallel-plate capacitor (as shown in Figure 1); a generic configuration typically appears in electrophotographic process. When an electric field of strength E is applied to move the charged toner particle from its residing surface to the other electrode, several mechanisms come into play. A major component of the electrostatic adhesion force arises from the attraction of the net charge on the particle and consequent image charges induced on the other side of the material surface on which the particle resides. The interaction between the net particle charge and externally applied electric field gives rise to the Coulomb force that tends to move the particle away from its residing surface. Moreover, an adhesive component of the electrostatic force arises from the attraction among the induced dipole as well as multipoles in the dielectric particle and there image charges on the other side of the particle residing surface, although it is rather weak in the case of charged toner particles.

In general, the electrostatic force on a charged toner particle can be written in a dimensionless form consisting of three components as[18, 19]

$$F_E = -\alpha\,\sigma^2 + 4\,\beta\,\sigma - \gamma, \qquad (1)$$

where the dimensionless average surface charge density is defined as

$$\sigma = Q/(4\,\pi\,\varepsilon_0\,R^2\,E), \qquad (2)$$

and the electrostatic force F_E is made dimensionless when measured in units of $(\pi\varepsilon_0 R^2 E^2)$. Here ε_0 is the permittivity of the medium surrounding the particle, i.e., air. The three coefficients α, β, and γ are always dimensionless, even when the equation for electrostatic force is written in a dimensional form,[7,10,18,19] and are functions of the particle dielectric constant, the spacing between the electrodes, charge distribution on the particle, etc.

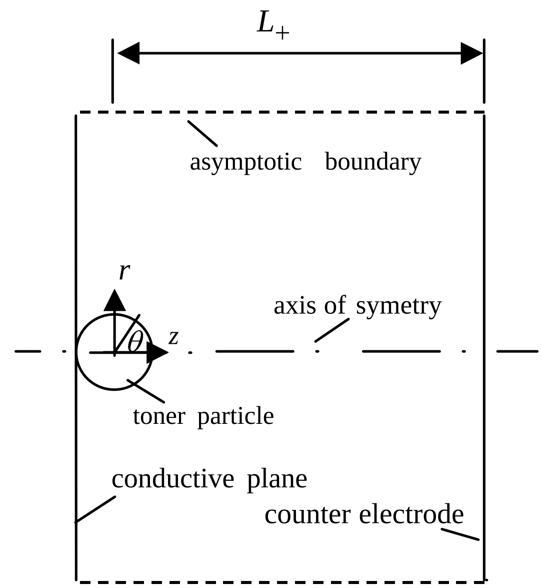

Figure 1. Definition sketch of a toner particle resting on one of the electrodes in a parallel-plate capacitor

To compute the electrostatic force on a charged particle according to (1), the three coefficients α, β, and γ must be evaluated. To determine the values of α, β, and γ, the Galerkin finite-element method for solving boundary-value problems as described by Feng and Hays[18] has been found to be effective, especially for complicated problem configurations involving several material interfaces. The same method is used in the present work.

Computational Results

For simplicity, the problem considered here is axisymmetric, representing the situation where the charge is distributed in the cap regions around two opposing poles on the spherical particle surface, as the surface charge density given by

$$\sigma/(1 - \cos\theta_c) \qquad (3)$$

for $0 < \theta < \theta_c$ and $\theta_c < \theta < \pi$ and zero everywhere else. Here θ_c denotes the polar cap half angle and the polar angle measured from the z-axis. In terms of dimensionless variables, the length such as the spacing between the electrodes L_+ is measured in units of the particle radius R.

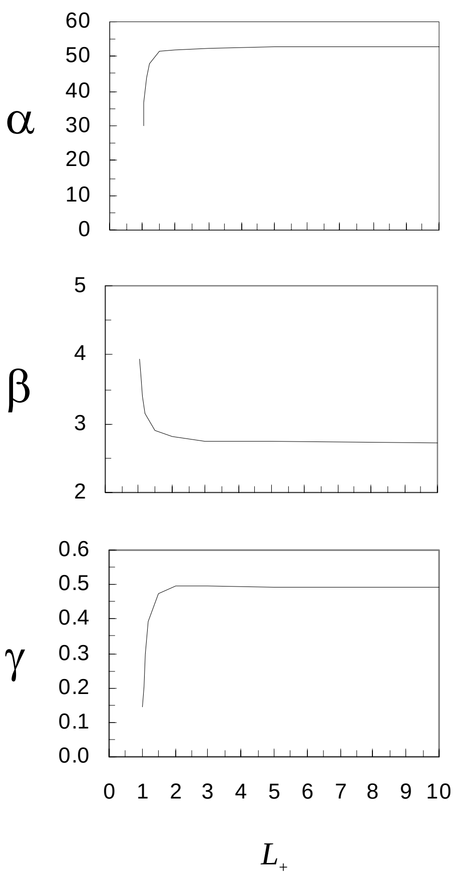

Figure 2. Variations of α, β, and γ versus L_+ for a spherical toner particle with dumb-bell type charge distribution

Here, the particle dielectric constant κ_p is assumed to be 3, as is a representative value for typical electro-photographic toner particles. For the case of a particle resting on a conductive plate ($L_+ = 10$), the computational results yield $\alpha = 1.592$ for a uniformly charge distribution (as if with $\theta_c = 90^o$) and $\alpha = 52.704$ for a dumb-bell type charge distribution with $\theta_c = 10^o$. Thus, we assume $\theta_c = 10^o$ in the present computations as a reasonably representative for triboelectrically charged toner particles, in view of that the magnitude of corresponding electrostatic adhesion force is comparable with most experimental findings.

Figure 2 shows the computationally determined values of α, β, and γ as functions of L_+. Qualitatively consistent with the results for a uniformly charged dielectric sphere[18], α for a spherical toner particle with nonuniform charge distribution decreases whereas β increases with reducing L_+ and γ varies nonmonotonically with L_+ for reasons discussed by Feng and Hays[18]. Noticeable variations in α, β, and γ for a toner particle with a dumb-bell charge distribution, however, only occur when $L_+ < 2$, i.e., the counter electrode is less than one particle diameter away from the center of the particle. Thus, the behavior of electric field detachment of a triboelectrically charged toner particle is expected to be insensitive to the spacing between the two electrodes in a parallel-plate capacitor, unless the spacing becomes so small that the counter electrode is nearly touching the particle.

Electric Field Detachment of Toner Particles

As indicated in (1), two roots of σ (denoted here by σ_1 and σ_2) exist when F_E is set to zero, corresponding to two threshold values for electric field detachment of the particle to take place. As discussed by Feng and Hays[18], σ_1 and σ_2 describe two extreme situations; one is when the net charge [first term on right side of (1)] becomes the dominant source of adhesion while the other is when the field-induced polarization [third term on right side of (1)] becomes dominant. Described with a parabolic curve, the net electrostatic force F_E is positive in the interval of $\sigma_2 < \sigma < \sigma_1$ and negative when σ is outside this interval. Thus, for electric field detachment to occur, the necessary condition $\sigma_2 < \sigma < \sigma_1$ must be satisfied.

For a particle with a dumb-bell type charge distribution in the case of $L_+ = 10$, the computed values for σ_1 and σ_2 are 0.1416 and 0.0658, respectively. If the charge on the particle surface becomes uniformly distributed (i.e., $\theta_c = 90^o$), we obtain 3.3915 and 0.0908 for σ_1 and σ_2, respectively. Clearly, a uniformly charged particle tends to have much greater latitude for electric field detachment than one with a nonuniform charge distribution, as also generally shown by Feng, Eklund and Hays[19]. In typical electrophotographic applications, we have $R = 5\text{x}10^{-6}$ (m) and $|Q| = 10^{-14}$ (C). According to (2) with $\sigma_1 = 0.1416$, $|E| > 2.54\text{x}10^7$ (V/m) is required to detach a triboelectrically charged toner particle from a conductive surface. If the particle charge is uniformly distributed, a field strength of $|E| > 1.06\text{x}10^6$ (V/m) (for $\sigma_1 = 3.3915$) might be sufficient to detach the particle.

Noteworthy here is the importance of the average surface charge density on a particle $Q/(4\pi R^2)$, in terms of electric field detachment physics, rather than Q/M (or $3Q/(4\pi\rho R^3)$) as is a commonly-referred-to parameter in electrophotography. The theoretical implication of (1) is that if all the toner particles are charged according to $Q \sim 4\pi R^2$ and have the same orientation on a surface with respect to their charge patches, the field strength for toner detachment should be the same regardless of the particle size difference.

Typical triboelectrically-charged toner particles, however, are found to actually follow a relationship somewhere between $Q \sim R^2$ and $Q \sim R$, although $Q \sim R^2$ is commonly assumed in most model calculations[20]. Thus, among a distribution of toner particles, larger particles may be more easily detached by an electric field than smaller particles. Yet, the general behavior of toner particles in electric field detachment should be independent of the mean particle size, because the comparison among toner of different batches indeed show a $Q \sim R^2$ relationship in terms of mean values[21].

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Biography

James Q. Feng received his B.S. in Chemical Engineering and M.S. in Physics from Tsinghua University in Beijing, China in 1982 and 1984, respectively, and his Ph.D. in Atmospheric Sciences from the University of Illinois at Urbana-Champaign in 1991. He then worked on electrostatic effects in continuous liquid coating at the University of Minnesota and electrohydrodynamics in multiphase separation processes at Oak Ridge National Laboratory. Dr. Feng joined Xerox WCR&T in 1995 working on electrophotographic marking science and technology. His current interests are in digital printing related electrostatic physics, electrohydrodynamics, as well as fluid mechanics. E-mail address – jfeng@wrc.xerox.com