Minimum dc electric field requirements for removing powder layers from a conductive surface

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An electrostatic powder dispenser was constructed to dispense particles without the use of a carrier gas. This device consisted of two contoured, outer stainless-steel plates that were electrically grounded and a flat, inner copper grid that was electrified and contained a central powder reservoir. Experiments were performed to investigate the levitation of various powders from the reservoir in the presence of an applied dc electric field. Eleven materials including metals, oxides, and conductively coated oxides were studied under vacuum and atmospheric conditions. The electric field required to remove particles from the powder reservoir was found to be a function of particle density and size. An equation was developed that predicted the minimum voltage necessary to remove conductive particles larger than 10 μm in diameter from a conductive surface in a vacuum environment: $E = [4.85(\rho D)^{1/2} + 0.362] \times 10^5$, where E is the field strength (V/m), ρ is the particle density (kg/m^3), and D is the mass median particle diameter (m). For particles in this size range, gravitational and electrostatic forces appeared to dominate, whereas for particles with a mass median diameter less than 10 μm, adhesive forces appeared to dominate. This equation was also found to hold for the removal of glass beads in air. A semiquantitative model was developed that was consistent with experimental results. This model calculated the force and charge induced on the particles in an electric field while taking into account the neighboring particles.

INTRODUCTION

The levitation of particles from a conductive surface has been studied for over 30 years. The experiments of Wuerker, Shelton, and Langmuir [1] demonstrated that with a sufficient electric field, conductive iron and aluminum particles could be levitated from a surface. This principle was also used as part of a particle charging and injection system developed by Shelton, Hendricks, and Wuerker[2] to electrostatically accelerate micron-diameter iron spheres to hypervelocities, on the order of km/s. It was also utilized under more benign conditions by Adamo and Nanevicz[3] in a device to control the dispensing of solid, conductive copper, silver, and silver-coated polyethylene micrometer-size particles in a vacuum. There has also been considerable work done both theoretically and experimentally to elucidate the mechanisms of contact charging that occur inside such a device (for example, see Cho,[4] Hendricks,[5] and Colver [6]). More recently, because of a need in the semiconductor industry to remove unwanted particles from microelectronic circuit board surfaces, attention has focused on studying the adhesion of individual particles on conductive surfaces, as described by Ranade[7] and by Cooper, Wolfe, and Miller.[8]

The work described in this paper is part of an overall study to develop a device [hereby designated as an electrostatic powder dispenser (EPD)] to continuously disperse particles without a carrier gas and with high efficiency under either atmospheric or vacuum conditions. In this light, it departs from the aforementioned studies in that it considers the continuous dispensing of many particles at moderate velocities, on the order of 0.1–10 m/s.

The EPD is a device consisting of two outer stainless-steel plates and an inner copper plate. It works well for most conductive particles in a vacuum and for most conductive and some dielectric powders in air. The device operates on the principle of electrostatic levitation. The powder is placed on a conductive plate in an electric field. The field induces a charge on the particles. This charge is a function of the applied field and the particle size. For sufficient electric fields, the particles are removed from the surface, travel to the oppositely charged electrode, and repeat the process until the particles are ejected from the outlet of the device.

This paper presents the requirements necessary to levitate powders from a conductive surface in the presence of an applied dc electric field. The results of experiments on particle levitation from a powder bed contained in the reservoir of the EPD are presented. An equation is presented that adequately predicts the experimentally determined minimum electric field necessary to remove larger (> 10 μm diameter) conductive particles from the conductive surface. Further, a theoretical model is proposed that determines the force and charge that are induced on particles in an electric field in the presence of other particles. This model is compared to experimental observations.

THEORY

A single particle in contact with a conductive surface and exposed to an electric field will acquire a charge distribu-

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tion that can be calculated from basic electromagnetic theory.[9] For a conductive particle, the acquisition of the charge induced by the field resides on the surface of the particle and is nearly instantaneous. The integration of this surface charge yields the total charge on the particle

$$q = \epsilon_0 \pi^3 D^2 E/6, \tag{1}$$

where $E = V/d$, electric field strength (V/m), D is the particle diameter (m), V is the applied voltage (V), d is the electrode separation distance (m), and ϵ_0 is the permittivity of free space (8.85×10^{-12} F/m). This calculation agrees with the results given by Shelton, Hendricks, and Wuerker,[2] Cho,[4] Myazdrikov and Puzanov,[10] and Adamo and Nanevicz.[3]

Next, usually it is assumed that the force on the sphere residing on a plane surface due to the electric field is identical to the force on a sphere separated from the surface:

$$F_q = \pi^3 \epsilon_0 D^2 E^2/6. \tag{2}$$

This is true if the sphere is far removed from the plane where it is in a uniform electric field. However, the surface charge distribution for the sphere in a uniform electric field is different from the surface charge distribution for a sphere resting on an infinite plane. Thus, the force on the sphere while resting on an infinite plane is not the same as that in a uniform electric field.

The surface charge distribution for the sphere that is resting on an infinite plane can be solved as a sum of a series. This series then can be used to find the total induced charge on the sphere that agrees with previous results. This can be utilized further to find the total lifting force, i.e., the total of the force component that is parallel to the normal vector of the plane, acting on the sphere. This summation and integration can be done numerically and gives a lifting force

$$F_e = 1.37 \pi \epsilon_0 D^2 E^2, \tag{3}$$

which is 0.83 times the force given in Eq. (2). Therefore, a larger electric field is needed to lift a sphere from the plane than that which normally is assumed.

When the lifting force exceeds the combined forces of gravity and adhesion, the particle will be levitated from the surface. Mathematically, identifying g as the gravitational acceleration,

$$F_e > mg + F_a. \tag{4}$$

The adhesive force, F_a (in N), can be derived from a theoretical basis,[11] where

$$F_a = HD/r^2, \tag{5}$$

with H as the Hamaker constant (J) and r the minimum separation distance (m). Experimental values for H range from 0.01×10^{-19} J to 230×10^{-19} J. Separation distances can range from as close as 0.4 nm to over 20 nm. Because this theory predicts adhesive forces that are uncertain over several orders of magnitude, empirical expressions such as that developed by Hinds[12] are more widely used

$$F_a = 0.15D\,[0.5 + 0.0045(\text{percent relative humidity})], \tag{6}$$

where F_a is in N and D is in m. However, Zimon[13] points out that the general application of a single empirical equation is incorrect because each expression developed is very dependent on the measurement method. Not only can the constants be found to vary, but the functional dependence on the particle size D can vary as well. In addition to the linear relationship with D, as given above, the adhesive force has been found to vary as the inverse of D, the inverse of D^2, and the inverse of $D^{0.7}$. Clearly, a general prediction of the adhesive force is very difficult. Fortunately, there is a region of particle size where the adhesive force can be neglected. This will be discussed in the results section.

The previous discussion has only considered a single particle. If the particle is in a reservoir of other particles, it will have some neighbors. If the neighbors are close enough, they will change the surface charge distribution and the lifting force on the particle. The exact surface charge distribution and the lifting force will depend critically on the arrangement of the neighbor particles, which makes the problem difficult.

A simpler problem can be considered. In this problem the particle is taken to be a hemisphere and its neighbors are taken to be the surface of revolution about the vertical axis as shown in Fig. 1. Because the model surface does not have the gaps that are formed by the neighboring spheres that touch the particle, it is expected that the lifting force found in this model would be less than the lifting force if the neighbors were spheres. Therefore, the lifting force found here should be a lower limit for a particle of a given radius and electric field. If this force is equated to the sum of the gravitational force and the adhesion force to calculate the electric field to lift the particle, the resultant electric field would be the upper limit needed to lift the particle.

The surface charge distribution can be found by dividing the surface into a number of concentric rings with a width and a slope to follow the surface. If the charge on each of these rings is known, then the potential can be found anywhere. By imposing the boundary conditions that the sur-

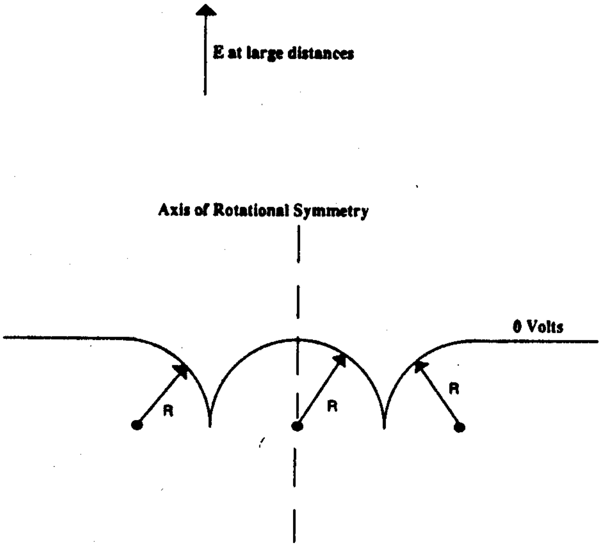

FIG. 1. Schematic representation for a simple model of a particle surrounded by neighbors.

face is at zero potential and the electric field is uniform at large distances, the charge on each of the rings can be determined. This procedure is used to solve the fields for electrostatic lenses.[14] The lifting force and the charge on the particle can be calculated once the charge on each ring is found. The charge on the particle is

$$q' = 0.23\pi\epsilon_0 D^2 E \tag{7}$$

and the lifting force is

$$F_e' = 0.11\pi\epsilon_0 D^2 E^2. \tag{8}$$

Equations (1) and (7) define the limits on the charge of a particle in an electric field surrounded by neighboring particles. This broad range for the charge on a particle can be refined by more qualitative arguments. For perfect spheres and a maximum packing fraction, the integration of the surface charge will be only over approximately 2π as opposed to 4π in the single, isolated particle case. This implies the value for the integrated charge on a particle should be about half of that given by Eq. (1), i.e.,

$$q = 0.824\pi\epsilon_0 D^2 E. \tag{9}$$

The force then should be found to be approximately half of the value given by Eq. (3). Analysis of experimental results in later sections will provide quantitative support for this assumption that

$$F_e = 0.68\pi\epsilon_0 D^2 E^2. \tag{10}$$

Consider the particles to be residing in a device schematically described in Fig. 2. Once the particles are removed from the first surface (the center electrode), they will exchange charge upon contact with the opposing (top) electrode, leave and continue "bouncing." The bottom electrode is shaped so that the bulk motion of the particles will be directed towards the exit aperture. When the particle is resting on the bottom electrode, the direction of the lifting force is normal to the surface of the bottom electrode. Thus, the initial direction of the trajectory that the particle will take from the bottom plate to the top plate is along this normal. A curved field line can be associated with this normal and with the initial position of the particle. The electric field vector at any point on this field line is tangent to the line. The particle will initially try to follow this field line, but as the velocity increases the centrifugal force will cause the particle to move away from the center of curvature of the field line. This motion away from the center of curvature of a field line will occur when the particle travels from the top plate to the bottom plate. Therefore, as the particles bounce between the plates, the bulk motion will be away from the center of curvature of the field lines. In the upper part of the dispenser, the centers of curvatures of the field are directed radially away from the reservoir dish. Similarly, in the lower or exit chamber the bulk particle motion will be directed radially toward the exit hole. This is usually accomplished by simply changing the electrode separation spacing so that the minimum field strength occurs at the dispenser exit.

The theoretical analysis detailed above implies two practical consequences. First, while Eq. (10) is true for the first removal of a particle from the powder bed, as the particle bounces through the device toward the exit, the probability that a particle will land and be reejected as a single, isolated particle is increased. This implies that for calculating exit conditions such as power and velocity, Eq. (3) must be used, but for calculating initial parameters such as minimum operating voltage, Eq. (10) must be used. Second, the inclination angle of the electrodes cannot result in separation spacings that would reduce the electrostatic force on the particle to values below that required by Eq. (3). In practice, force values somewhat less than those given by Eq. (3) are acceptable for continued 'bouncing' due to a coefficient of restitution for quasi-elastic collisions.[6]

EXPERIMENTAL DESCRIPTION

Experiments were performed using the device that is shown schematically in Fig. 2. The two outer electrodes were held at the same potential, usually electrical ground. The inner, center electrode consisted of a copper wire mesh (wire diam = 0.305 mm, hole area = 1.73 mm^2) having approximately 64% open area and supporting a plate or shallow dish in the center. This inner electrode was held at a different potential, usually at the output potential of a high-voltage power supply. Characteristic dimensions of the device are given in Table 1.

Various known quantities of powders were placed in the central dish. The resultant powder beds ranged in depth from on the order of a monolayer to 4 mm. Powder parameters qualitatively were determined photographically through a Zeiss microscope and quantitatively were deter-

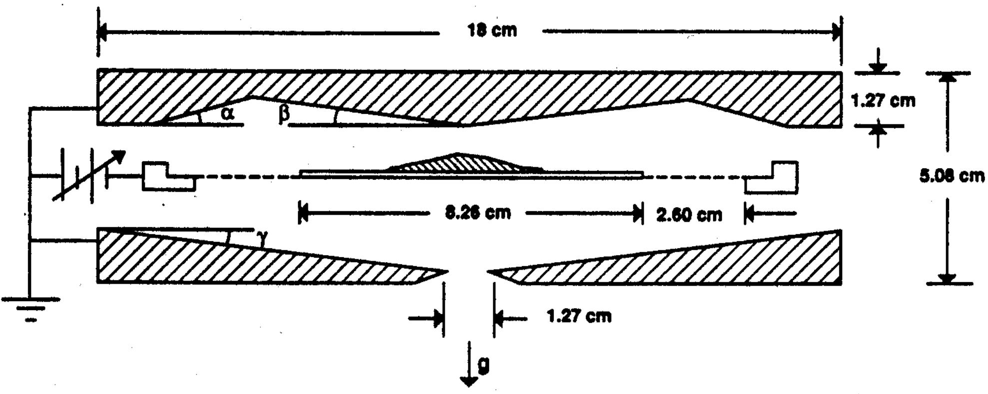

FIG. 2. Schematic of electrostatic particle dispenser.

TABLE I. Physical characteristics of electrostatic powder dispenser (EPD).

Diameter	18.1 cm
Height	5.08 cm
Weight	1.2 kg
Electrode separation	1.27 cm
Outlet diameter	1.27 cm
Electrode angle: α	10.0 deg
β	5.4 deg
γ	8.2 deg
Electrode Material: Outer electrodes	SS
Inner electrode	Cu
Dish volume	3.5 cm^3
Screen mesh	Cu 0.305-mm wire diam 1.73-mm^2 hole area

TABLE III. Powder removal efficiencies. Note: Separation spacing between powder layer and upper electrode is 0.0127 m.

Material	Particle diameter (μm)	Voltage (kV)	Maximum removal efficiency
Ag-clad TW	4.55	10.5	49%
Ag-SF-14	57	10.0	96%
Ag-SF-44	31.5	3.5	100%
Brass	135	8.0	100%
Cu dust	12	4.0	98%
Cu-SG	90	7.5	97%
Glass	46.5	8.0	97%
Graphite	1	5.0	18%
W-Re	3.7	10.0	34%
Zinc	14.5	5.0	98%

mined using either a Leeds and Northrop Model 7995-93 Microtrac[15] or a Micromeritics Model 5000 Sedigraph[16] particle size distribution measuring device. A voltage typically was supplied to the inner electrode, establishing an electric field between the inner electrode and the grounded outer electrodes. The voltage that produced the first observable stream of particles from the device was recorded and denoted as the minimum voltage. The dispensing efficiency of the device was determined by weighing the collected powder dispersed and comparing it to the initial weight for a given voltage. Output number median particle diameters were measured *in situ* with an Insitec PCSV[17] system.

While some experiments were performed in air, most were performed inside a vacuum chamber. Operation inside a vacuum chamber was important to minimize or to eliminate the component of the adhesive force due to the surface tension effects of interstitial condensed water vapor.

EXPERIMENTAL RESULTS

Table II presents a list of some of the powders tested and measurements of the particle size parameters with the techniques discussed in the previous section. A number of key points are evident from Table II. First, the qualitative measurement of particle size using microscopy corresponds quite well with the mass median particle sizes determined by either the Microtrac[15] or Sedigraph.[16] Even for high aspect ratio particles such as copper flakes, the equivalent spherical diameter calculated from the mass photographic size of 44 μm in diameter by 1 μm thick is 14 μm, which is only 14% larger than the value of 12 μm determined by the Microtrac.[15] Second, it is evident from the missing entries in Table II, that insulators are impossible to dispense in a vacuum for electric fields less than 20 kV/cm, which was the approximate breakdown limit of the dispensing device.

TABLE II. Material diameter comparison.

Material	Photographic median (μm)	Mass median measured (μm)	Number median calculated (μm)	Number median measured (μm)
Copper flake	44.3 (44×1)	12.0	4.01	3.52
Ag-clad TW	5.60	4.55	3.52	2.40
Metalite-Ag (SF-44)	31.7	31.5	25.3	29.9
Cerium oxide	2.70	2.60	0.30	···
Glass beads	45.9	46.5	36.0	···
W-Re	4.80	3.67	1.41	1.69

Table III lists the maximum removal efficiency found for the various materials tested. The removal efficiency is defined as the mass of material removed from the powder reservoir divided by the initial mass of material in the reservoir. The diameter of the individual particles and the voltage necessary to obtain the maximum removal efficiency are also listed. The larger conductive particles demonstrated very sharp efficiency curves that were consistent with the shape of efficiency curves for conductors determined by Zimon.[13] The dispensing efficiency of the copper dust, as defined earlier, versus voltage is shown in Fig. 3. The maximum remov-

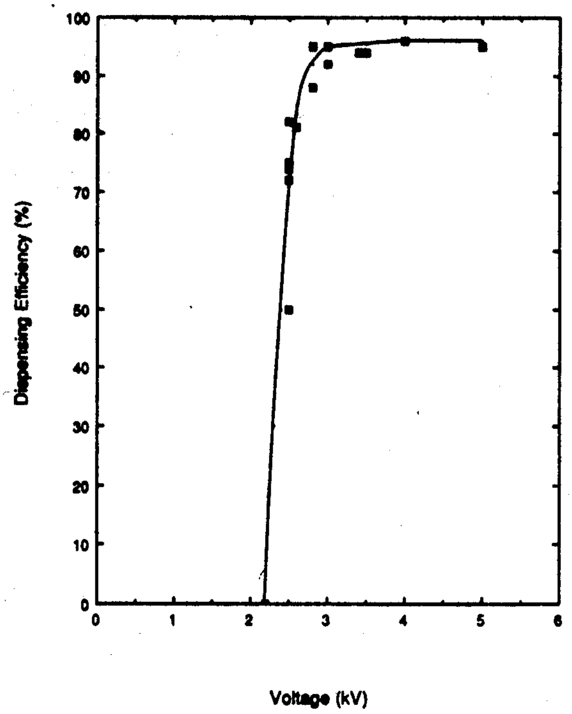

FIG. 3. Dispensing efficiency vs final voltage for copper dust.

al efficiencies of most of the powders tested are plotted versus their particle size in Fig. 4. The inability to efficiently remove particles having diameters less than 10 μm is attributed to the dominance of the adhesive force over the electrostatic and gravitational forces.

Reconsider Eq. (10) which was a qualitative estimate of the minimum force required to electrostatically remove a particle from a powder layer. Substitution into Eq. (4) yields

$$0.68\pi\epsilon_0 D^2 E^2 = mg + F_a. \tag{11}$$

Realizing that Fig. 4 implies that the adhesive force is not a significant factor for larger particles, the adhesion term in Eq. (11) can be neglected. Solving for the minimum field strength

$$E = 5.21\times 10^5 (\rho D)^{1/2}. \tag{12}$$

Table IV provides a list of powder materials used, the particle mass median equivalent spherical diameters and density, and the minimum voltage required to dispense the powder in vacuum and in air for some materials.

The minimum field strength, regardless of polarity, is plotted against $(\rho D)^{1/2}$ in Fig. 5. All the data points, except for the W-Re and Ag-Clad TW, and graphite data fall within 16% of a line defined by a least-square fit to the data:

$$E = [4.85(\rho D)^{1/2} + 0.362]\times 10^5. \tag{13}$$

The agreement to within 10% between Eqs. (12) and (13) is considered to be serendipitous because Eq. (12) was not derived rigorously from theory. The nonzero intercept is probably the result of experimental uncertainties. The three points not following a $(\rho D)^{1/2}$ dependence are the smallest diameter particles tested. This confirms that for large particles ($D >$ 10 μm), particle adhesion is dominated by the gravitational and electrostatic forces. Furthermore, Eq. (13) has been shown that it can be used to accurately predict the minimum field required to electrostatically levitate particles greater than 10 μm in diameter from a powder layer. Equation (13) does not hold for particle diameters below 10 μm because of the increasing significance of the adhesive force.

TABLE IV. Minimum dispensing voltage.

Material	Particle mass median diameter (μm)	Particle density (kg/m^3)	$V_{\rm min}$ (kV) Air	$V_{\rm min}$ (kV) Vacuum
Ag-clad TW	4.55	3400	···	8.0
Ag SF-14	57	850	2.2	1.2
Ag SF-44	31.5	850	3.0	1.0
Al SF-12	80	···	5.0	5.0
Brass	135	9404	7.0	7.0
Cu dust	12.0	9977	4.5	2.5
Cu-SG	90	825	3.0	2.0
Glass	46.5	2547	3.3	···
Graphite	1	2260	···	5.0
Stainless steel	50	8000	4.6	5.0
W-Re	3.67	20 000	···	4.5
Zinc	14.5	7140	N.A.	2.6

At this point it should be noted that included in the data is the minimum voltage required to disperse glass particles in air. Table IV indicates that these glass particles could not be dispersed in a vacuum. One hypothesis that might explain this observation is that the ionization of the gas provides the mechanism for charge transfer for insulating glass particles

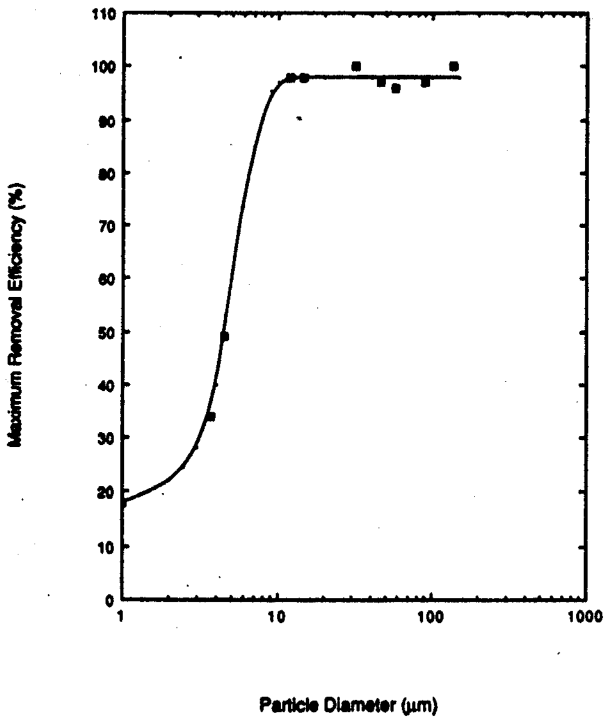

FIG. 4. Maximum removal efficiency vs mass median particle diameter.

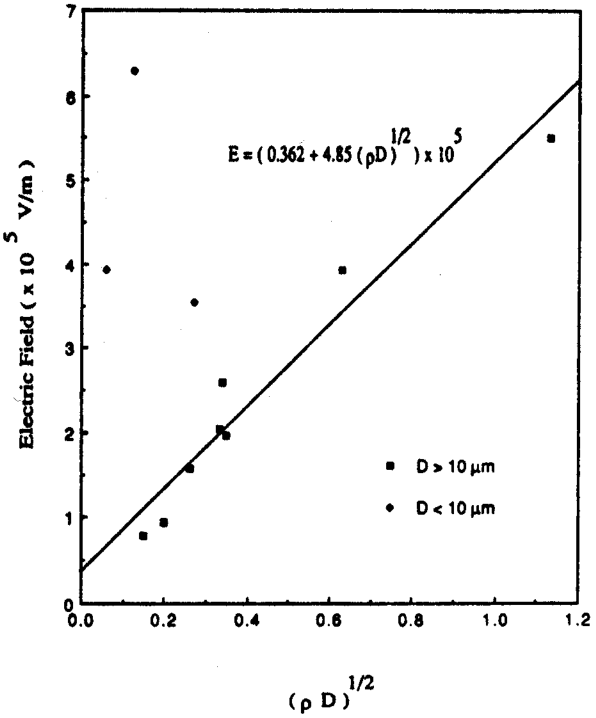

FIG 5. Minimum electric field intensity necessary to levitate particles.

in air. In a vacuum, no ions or an insufficient number are present, so that the insulating particles have no method of acquiring charge. Another possibility is that the moisture in the air causes interstitial water to form between particles and on their surfaces, thereby creating a conductive path and allowing the particles to be dispersed in air. Because the data for glass in air also follows Eq. (13), it appears reasonable to assume that the equation not only holds for any conductive particle larger than 10 μm in diameter but also holds for dielectric particles larger than 10 μm in diameter in the presence of a ionizable gas. This would be consistent with observations on dielectric particle levitation in air made by Colver.[6]

SUMMARY

The mass efficiencies and the minimum voltages required for the removal of powders from a conductive surface by means of an electrostatic field were measured. The interpretation of the efficiency data led to the conclusion that the adhesive force does not play a significant role when electrostatically levitating particles greater than 10 μm in diameter against gravity. The minimum voltage data led to the relationship that accurately predicts the minimum voltage required to remove a powder layer from a surface if the equivalent spherical mass medium particle diameter and density are known. This empirical relationship was shown to be consistent with the developed theory.

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