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Article

The Role of Humidity on the Lift-off of Particles in Electric Fields

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Partículas podem ser separadas em campos elétricos quando forças eletrostáticas ultrapassam a força devido à gravidade. Para partículas condutoras, o *lift-off* ocorre quando o campo elétrico gera carga a ser transferida de uma superfície aterrada para a partícula, e a partícula carregada é então separada no campo elétrico; este mecanismo ocorre com qualquer polaridade do campo elétrico. Para partículas isolantes perfeitas, esta transferência de carga não pode ocorrer, mas as partículas que já estão carregadas podem ser separadas por um campo elétrico de polaridade apropriada (mas não outra polaridade). Experimentos foram conduzidos, em condições ambiente e controlados ambientalmente, nos *lift-off* de partículas compostas de diferentes materiais, e os resultados para os necessários campos elétricos limites para o *lift-off* foram comparados a previsões baseadas em modelos de partículas condutoras e isolantes. Os resultados para uma partícula de alumínio estão em acordo com o modelo de partícula condutora. Nos casos de partículas isolantes, a separação das partículas de politetrafluoretileno (PTFE) mostra-se consistente com o modelo de partícula isolante, mas partículas de Nylon® e de vidro exibiram comportamento dependente da umidade. Em baixa umidade, partículas de Nylon® e de vidro são separadas de acordo com o modelo de partícula isolante, enquanto que à umidade elevada, o comportamento de separação surpreendentemente seguiu o modelo de partícula condutora. Sugere-se que a elevada umidade, a natureza hidrofílica das superfícies das partículas de Nylon® e de vidro levou à formação de uma camada superficial condutora que facilita a transferência de carga do mesmo modo que uma partícula de metal.

Particles can be lifted in electric fields when the electrostatic forces overcome the force due to gravity. For conducting particles, the lift-off occurs when the electric field causes charge to be transferred from a grounded surface to the particle, and the charged particle is then lifted in the electric field; this mechanism occurs with either polarity of the electric field. For perfectly insulating particles, this charge transfer cannot occur, but the particles that are already charged can be lifted by an electric field of the appropriate polarity (but not the other polarity). Experiments were carried out, under ambient and environmentally controlled conditions, on the lift-off of particles composed of different materials, and the results for the threshold electric fields necessary for lift-off were compared with predictions based on the conducting and insulating particle models. Results for an aluminum particle are in agreement with the conducting particle model. In the case of insulating particles, the lifting of polytetrafluoroethylene (PTFE) particles is consistent with the insulating particle model, but Nylon® and soda-lime glass exhibit humidity-dependent behavior. At low humidity, Nylon® and soda-lime glass particles are lifted in accordance with the insulating particle model, while at high humidity, the lifting behavior surprisingly follows the conducting particle model. It is suggested that at high humidity, the hydrophilic nature of the Nylon® and soda-lime glass particle surfaces leads to a conducting surface layer of water that facilitates charge transfer similar to a metal particle.

Keywords: electrostatic charge, humidity, lift-off

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Introduction

It is well known that humidity plays an important role in electrostatic charging.[1] For example, electrostatic effects are noticed in daily life much more frequently in drier conditions, which can be attributed to water layers that develop on surface at high humidity and allow charge to "leak away". Recent experiments by Galembeck and co-workers[2,3] have shown that humidity effects are even more confounding, and that changes in humidity alone (without contact with other surfaces) can increase the electrostatic charge on a surface. In this work, our group addresses the role of humidity in a new context, the lifting of particles in electric fields.

The intersection between electrostatics and particle flow can lead to complex behavior.[4,5] Particles become electrostatically charged as they flow due to collisions and rubbing with other particles and other surfaces. The electrostatic charge can alter the behavior for small particles, in which case the electrostatic forces combined with the small particle mass can cause particles to adhere to walls or become lifted in electric fields. For example, in industrial systems such as fluidized beds, particle adhesion to walls causes problems that ultimately require process shut-downs.[6] In dust storms, electrostatic effects are believed to enhance the lifting of dust[7-9] due to the large electric fields that are developed in dust storms[10-12] and the charge carried by the particles.[13] This behavior is exploited in the abrasive coating industries, where the particles are charged by induction in order to be lifted by an electric field onto an adhesive backing.

This work addresses aspects of the electrostatic lift-off of particles in electric fields. For a conducting particle sitting on a conducting surface, lift-off occurs by induction. Consider, for concreteness, an electric field oriented such that the positive pole is up. A particle in the presence of this electric field will polarize such that its top is negative and its bottom is positive. If the bottom of the particle is in contact with a conductor, electrons will flow from the conductor to the particle to locally neutralize the bottom of the sphere. In this way, an initially neutral particle obtains a net negative charge and will thus be lifted in the electric field. The threshold value of the electric field needed for lift-off has been theoretically determined.[14,15]

For an insulating particle sitting on a conducting surface, the mechanism described above is not relevant as charge cannot flow from the conducting plate to the particle. However, if the insulating particle is already charged, this charge can cause it to be lifted in an appropriately oriented electric field (note that an insulating particle, in contrast to a conducting particle, can retain electrostatic charge when sitting on a conducting plate). In this case, the charged particle must overcome not only gravity but also the Coulombic attraction due to the image charge in the conductor. The threshold electric field required for lift-off has been rigorously determined with a multipole expansion method,[16] and also with a simpler but more approximate method.[17]

While electrostatic lift-off has been examined for idealized conducting and insulating particles, actual situations may be more complex. In particular, particles that are nominally insulating may have surface layers of adsorbed water that render the surfaces conducting. This effect is the reason why electrostatic phenomena are more apparent in arid conditions, as electrostatic charges are dissipated by conducting water layers in humid conditions. This work addresses the effects of humidity on the electrostatic lift-off of different types of particles.

Experimental

This study investigated the lift-off of spherical particles sitting on a conducting plate within an electric field oriented parallel to the direction of gravity. The electric field was created by two circular copper plates 15 cm in diameter separated by a distance d; the distance d was maintained using glass spacers (Figure 1). The bottom plate was electrically grounded and the top plate was connected to either a positive or negative high voltage dc source (Ultravolt Inc.) to create a voltage difference (ΔV) between the plates. The electric field between the plates is given by:

$$E = \frac{\Delta V}{d} \quad (1)$$

Both ΔV and d (distance between plates) could be varied in our apparatus, but results are presented here only for ΔV varied and d = 8.8 mm. The maximum voltage that could be applied is 10 kV, which corresponds to an electric field of approximately 1200 kV m^{-1}.

Experiments were carried out for four particle materials: aluminum, polytetrafluoroethylene (PTFE), Nylon® (McMaster Carr Inc.) and soda-lime glass (Jaygo, Inc), which were chosen to be representatives of a metal (aluminum), a hydrophobic insulating material (PTFE), and a hydrophilic insulating material (soda-lime glass). The sizes and masses of the particles are given in Table 1.

To carry out an experimental trial, a particle was placed on the bottom plate, close to the center of the plate. A voltage was applied, and incrementally increased in steps of 0.5 V every 5 s using a computer-controlled mechanism until the particle lifted. The minimum voltage that caused lift-off was recorded; the corresponding electric field

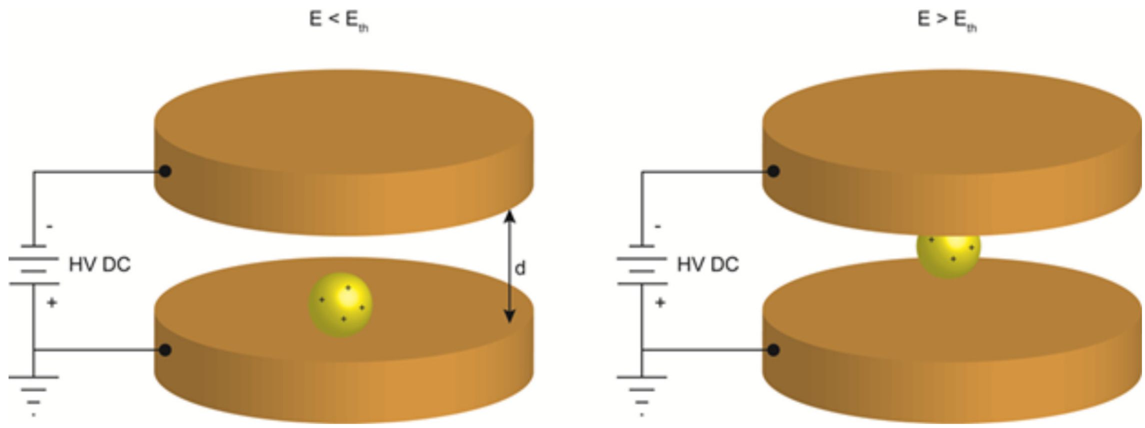

Figure 1. Schematic of experimental setup.

Table 1. Particle data and theoretical predictions for threshold electric fields

	Data			Modeled as conductor	Modeled as insulator
	mass / mg	d / mm	Q / nC	E_{th} / (kV m^{-1})	E_{th} / (kV m^{-1})
Aluminum	11.6	1.98		871	
PTFE	4.7	1.59	−0.13	693	725
Nylon®	2.6	1.59	0.14	515	565
Soda-lime	0.56	0.75	a	504	

[a]Did not measure charge; d: distance between plates; Q: charge on the particle; E_{th}: threshold electric field.

between the plates is referred to as the threshold electric field, E_{th}. As noted above, our apparatus can only apply electric fields up to 1200 kV m^{-1}. These experiments were then repeated both in air and in a glove box with a nitrogen environment to control humidity. Low humidity was defined as relative humidity below 10%, and high humidity was defined as relative humidity above 35%. The relative humidity was measured by a humidity probe (traceable hygrometer Fisher Scientific, Inc.).

The initial charge state of the conducting particle is not important since any charge on the particle will dissipate when placed on the grounded conducting plate. However, the initial charge state of the insulating particles may be important since these charges do not necessarily dissipate when the particle is placed on the grounded conducting plate (the charge will not dissipate for a perfect insulator; however, a surface water layer on an insulators can mediate the charge dissipation). To obtain a reproducible initial charge state, the insulating particles were shaken inside a glass bottle for a few seconds before being placed on the grounded plate. The charges on the insulating particles from this procedure were measured using a Faraday pail apparatus. The Faraday pail was connected to an electrometer (Keithley Inc., Model 6485) interfaced with a computer. The electrometer measures the current generated as the charged particle is dropped into the Faraday pail, and this current is integrated over time to obtain the charge.

Theoretical background

The forces acting on the particles are the gravitational force (F_g), the electrostatic force, (F_e) and the van der Waals forces (in addition, there may be capillary bridging forces due to moisture, but these will not be considered). The gravitational force is simply

$$F_g = -mg \tag{2}$$

where m is the mass of the particle and g is the gravitational constant. For an insulating particle, F_e depends on the particle radius (R), charge on the particle (Q) and dielectric constant (e_p). The electrostatic force has been rigorously addressed with a multipole expansion method.[13] However, the following simpler approximation[14] can be used

$$F_e = -\alpha \frac{1}{4\pi\varepsilon_0}\frac{Q^2}{R^2} + \beta QE - \gamma 4\pi\varepsilon_0 R^2 E^2 \tag{3}$$

where the first term corresponds to the attractive force between the particle charge with the image charge on the conducting plate, the second term corresponds to the force on the charged particle due to the electric field, and the third term corresponds to the attractive force between the dipole induced in the particle by the electric field and the conducting plate (note that this last term is relevant even for uncharged particles). For a particle sitting on the bottom plate, in air, the values of the parameters are $\alpha = \frac{1}{4}$, $\beta = 1 + \frac{\delta}{2}$, $\gamma = \frac{3}{8}\delta^2$ and $\delta = \frac{\varepsilon_p - 1}{\varepsilon_p + 2}$. By comparing with results from the multipole expansion method,[13] this approximation is found to be accurate to ca. 15%.

For a conducting particle, the electrostatic force is given by

$$F_e = \zeta\, 4\pi\varepsilon_0 R^2 E^2 \qquad (4)$$

where $\zeta = 1.37$.[11]

The van deer Waals forces were neglected since these forces are expected to be significantly smaller in magnitude (approximately 15%). In addition, van der Waals interactions depend on details of the surface roughness. The threshold electric field needed for lift-off is then determined by the condition $F_e = F_g$. The threshold electric field for the case of an insulating particle is

$$E_{th} = \frac{\beta Q - \sqrt{(\beta Q)^2 - 16\pi\gamma\varepsilon_0 R^2 \left(\alpha \frac{1}{4\pi\varepsilon_0}\frac{Q^2}{R^2} + mg\right)}}{8\pi\gamma\varepsilon_0 R^2} \qquad (5)$$

This root represents the threshold for lift-off when E is increased from zero. At very high E, the particle adheres to the plate due to the induction effect, and lift-off will occur when a threshold is reached by reducing E from very high values; this threshold value is given by the other root.

For the case of a conducting particle, the threshold electric field for lift-off is

$$E_{th} = \sqrt{\frac{mg}{\zeta\, 4\pi\varepsilon_0 R^2}} \qquad (6)$$

Theoretical predictions for E_{th} are given in Table 1 for the particles examined in our experiments.

Results and Discussion

The results for aluminum particles, which are conducting, are first addressed. Results from all experimental trials for aluminum particles at low and high humidity are shown in Figures 2a and 2b, respectively. The particles were lifted in all cases, at similar threshold electric fields for both positive and negative applied voltages, irrespective of humidity. The median values of the threshold electric fields are given in Table 2, and are found to agree well with the theoretical prediction given in Table 1. The experimental values are about 15% lower than the theoretical prediction, which may occur because the theoretical expression is derived in the case that the particle diameter is insignificant in regard to the gap between the plates, and this criterion is not fully satisfied in our experimental setup.

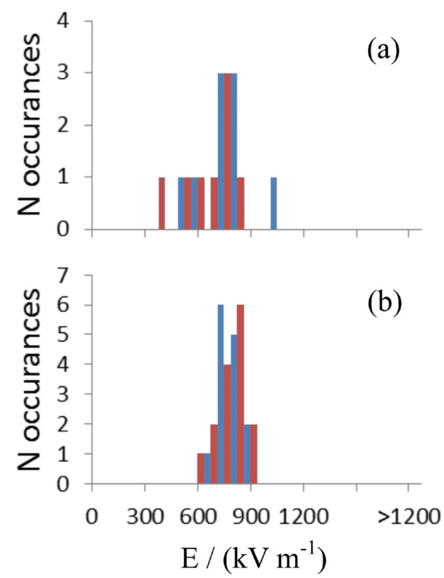

Figure 2. Distribution of electric fields causing lifting for aluminum particles. (a) RH < 10% and (b) RH > 35%. Red bars refer to negative voltages on upper plate, and blue bars refer to positive voltages on upper plate. Results for > 1200 kV m^{-1} correspond to the trials where the particle did not lift-off after reaching the maximum voltage.

Next, the results for PTFE particles, which are hydrophobic, are addressed. Results from all experimental trials for PTFE particles at low and high humidity are shown in Figures 3a and 3b, respectively. When a negative voltage was applied, the particles did not lift-off, even as the maximum electric field of 1200 kV m^{-1} was

Table 2. Experimental results for median values of threshold electric fields

	RH < 10%		RH > 35%		10% < RH < 25%	
	E_{th+} / (kV m^{-1})	E_{th-} / (kV m^{-1})	E_{th+} / (kV m^{-1})	E_{th-} / (kV m^{-1})	E_{th+} / (kV m^{-1})	E_{th-} / (kV m^{-1})
Aluminum	724	−679	755	−757		
PTFE	866	mu	820	mu		
Nylon®a	mu	mu	454	−476		
Nylon®b					mu	−631
Soda-lime	648	mu	366	375		

mu: median undefined, as particle did not lift-off in more than half of trials; E_{th}: threshold electric field. [a]Experiments in which charge dissipated; [b]experiments in which charge did not dissipate.

reached. In contrast, a positive voltage was found to cause particle lift-off with median electric field thresholds of 820 kV m^{-1} and 866 kV m^{-1} at low and high humidity, respectively. Thus, these results were insensitive to the humidity level.

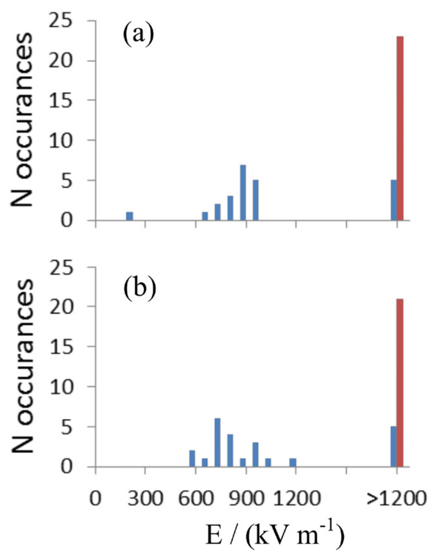

Figure 3. Distribution of electric fields causing lifting for PTFE particles. (a) RH < 10% and (b) RH > 35%. Red bars refer to negative voltages on upper plate, and blue bars refer to positive voltages on upper plate. Results for > 1200 kV m^{-1} correspond to the trials where the particle did not lift-off after reaching the maximum voltage.

The initial charge on the PTFE particles (after rolling in a glass beaker), as measured using a Faraday pail, is shown in Table 1. Using this value for the charge, the theoretical prediction for the E_{th} is obtained using the insulating particle model described above. The theoretical prediction and experimental result agree well, with the experimental value being about 15% higher. This difference may be due to the omission of the van der Waals adhesive forces in the theoretical model.

It is noted that the theoretical value for E_{th} of the PTFE particle based on the conducting particle model is also in reasonable agreement with experiment. However, this is just coincidence, because if the PTFE particle did in fact behave like a conductor it would be lifted with both polarities of applied voltage, but this did not occur in the experiments with PTFE particles.

Next, results for the Nylon® particles, which are hydrophilic insulators, are addressed. Results for all experimental trials with Nylon® particles at low and high humidity are shown in Figures 4a and 4c, respectively. At high humidity, the Nylon® particles lifted in all trials, independent of the polarity of the electric field. This result suggests that Nylon® behaves like a conducting particle at high humidity. In fact, the median values for the experimental E_{th} are in good agreement with the theoretical prediction based on the conducting particle model (within 10%). However, at low humidity, the Nylon® particles did not lift-off with the positive applied voltage, and rarely lifted with the negative applied voltage, for electric fields up to 1200 kV m^{-1}. This result indicates that at low humidity, Nylon® behaves like an uncharged insulating particle in these experiments.

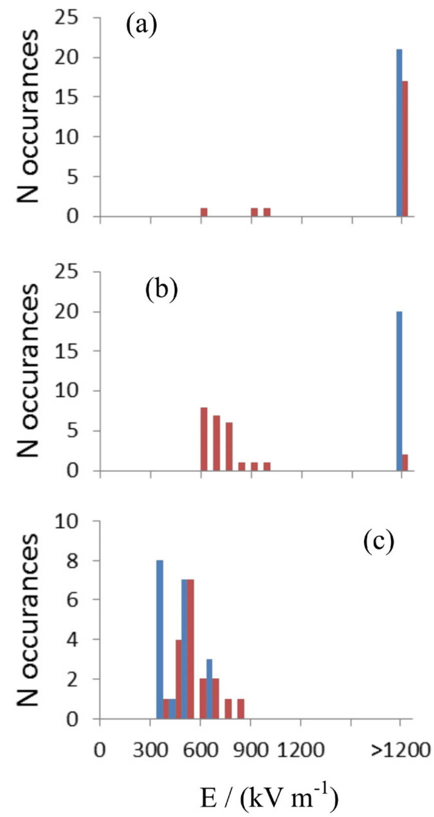

Figure 4. Distribution of electric fields causing lifting for Nylon® particles. (a) RH < 10%, (b) 10% < RH < 25% and (c) RH > 35%. Red bars refer to negative voltages on upper plate, and blue bars refer to positive voltages on upper plate. Results for > 1200 kV m^{-1} correspond to the trials where the particle did not lift-off after reaching the maximum voltage.

The behavior of Nylon® particles was investigated in more detail, in particular, why the Nylon® particles behaved as uncharged insulators when they were first rolled in a glass beaker to transfer charge. The low humidity experiments were carried out glove box; the difficulty in working with gloves meant that tweezers had to be used to transfer the particle from the glass baker to the conducting plate. The contact with the tweezers, as well as the time delay between the charging and the lift-off experiments, may have led to much of the charge on the Nylon® particles being dissipated (while the same procedure was used for the PTFE particles, this issue did not occur because Nylon® loses charge much more quickly than PTFE presumably due to a conducting water surface layer that forms because of its hydrophilic nature).

To address this issue, a series of trials were carried out for Nylon® particles outside the glove box on days when the relatively humidity was fairly low (10-25%). In this case, the particle was easily (and quickly) transferred from the glass beaker to the conducting plate by simply dumping the particle onto the plate; this quick and contact-free transfer allows the Nylon® particle to retain its charge. The results of these studies are shown in Figure 4b. With a positive applied voltage, the particles do not lift-off for electric fields up to 1200 kV m^{-1}, but the particles do lift-off with a negative applied voltage with a median value E_{th} of 631 kV m^{-1}. The fact that the particle lifts-off with only one polarity of applied voltage indicates that the lift-off is due to electrostatic charge initially residing on the particle rather than charging of the particle by induction. The particle charge was measured by Faraday pail experiments. Using this charge value, our theoretical prediction of E_{th} for lift-off based on the insulating particle model is in good agreement with experiment. The experimental value is about 12% higher than the theoretical prediction, with the difference likely due to the neglect of the van der Waals adhesive forces in the theoretical model.

Finally, results for soda-lime glass particles, which are also hydrophilic insulators, are addressed. For our low humidity experiments with soda-lime glass, an improved technique was used (in comparison to the Nylon® experiments) in which it was possible to set up the experiments without discharging the particles. However, the charge could not be measured with our apparatus at low humidity, and so there are not values for the charge of the soda-lime glass particles. Results for all experimental trials with the silica-lime glass particles at low and high humidity are shown in Figures 5a and 5b, respectively. As with Nylon®, the soda-lime glass behaves like a conducting particle at high humidity, and is lifted in almost all trials and at similar electric fields for both positive and negative polarities of the electric field. In our low humidity experiments, it was found that the soda-lime glass behaves like a charged insulator: a negative voltage rarely caused particle lift-off during the trial, but a positive voltage caused particle lift-off with a median electric field threshold of 648 kV m^{-1}.

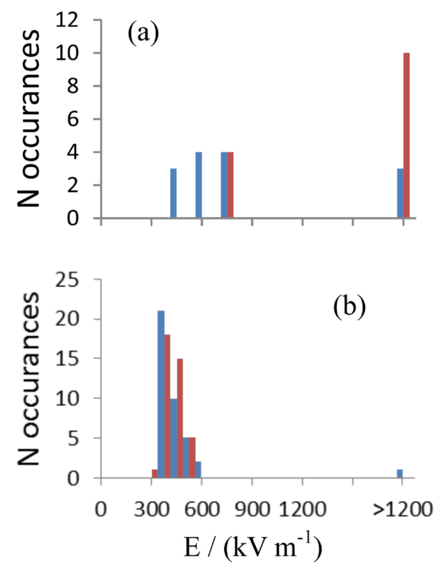

Figure 5. Distribution of electric fields causing lifting for soda-lime glass particles. (a) RH < 10% and (b) RH > 35%. Red bars refer to negative voltages on upper plate, and blue bars refer to positive voltages on upper plate. Results for > 1200 kV m^{-1} correspond to the trials where the particle did not lift-off after reaching the maximum voltage.

Conclusions

Our experiments address the role of humidity and particle wetting properties on the lift-off of particles in electric fields. The electrostatic lift-off process has been well understood, and the different mechanisms that apply for conducting and insulating particles have been previously described.[11-14] It is shown here that in regard to this lift-off, the characterization of a particle as conducting or insulating is not always straightforward. In particular, hydrophilic insulating particles can behave as insulators at low humidity, but as conductors at high humidity (examples of such particles include Nylon® or soda-lime glass). This occurs because the material is inherently insulating, but due to the hydrophobicity of the material a water layer forms on the surface at high humidity; this water layer is conducting, and due to this surface conduction the particle behaves like a conductor in regard to electrostatic lift-off.

These results have implications in regard to the lifting of soil particles in dust storms. An electric field will affect dust lifting very differently depending on whether the dust is conducting or insulating:[18] For neutral dust particles, the electric field creates a lifting force if the particles are conductors (equation 4), but a force that is cohesive to the surface if the particles are insulators (third term of equation 3). This effect was directly observed in wind tunnel experiments, where the particle remained the same between trials while the surface was switched between a conductor (copper) and an insulator (a plastic).[19] Our results show directly how humidity can change the behavior of a hydrophilic material from insulating to conducting; since soil particles are hydrophilic, they should exhibit this humidity-dependent behavior in electric fields.

Acknowledgments

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