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Cite as: AIP Advances 6, 035117 (2016); https://doi.org/10.1063/1.4944831
Submitted: 08 October 2015 . Accepted: 13 March 2016 . Published Online: 22 March 2016

L. Xie, N. Bao, Y. Jiang, and J. Zhou

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Effect of humidity on contact electrification due to collision between spherical particles

L. Xie, N. Bao, Y. Jiang, and J. Zhou

College of Civil Engineering and Mechanics, Lanzhou University, Lanzhou, Gansu, China, 730000 and Key Laboratory of Mechanics on Environment and Disaster in Western China, Ministry of Education, Lanzhou University, Lanzhou, Gansu, China, 730000

(Received 8 October 2015; accepted 13 March 2016; published online 22 March 2016)

This paper reports an experimental study of the contact electrification (CE) that happens when glass spheres of identical materials collide under different ambient relative humidity (RH) conditions. The experimental results indicate that the net charge on a sphere from a single collision is significantly altered by varying the RH level; the charge increases with increasing RH at low humidity, and then decreases at high RH conditions. The net charge reaches a maximum in the 20%–40% RH range. To explain the dependence of the CE on RH, we propose a model which yields predictions in agreement with the experimental data. The model also reveals how CE can be affected by temperature and surface absorption energy. © 2016 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution 3.0 Unported License. [http://dx.doi.org/10.1063/1.4944831]

I. INTRODUCTION

Ancient Greeks knew that certain objects, such as rods of amber, after being rubbed with cat’s fur were able to attract light objects like feathers;¹ this is possibly the earliest record of triboelectrification or contact electrification (CE).² Around 600 BC, Thales of Miletus made a series of observations on static electricity, but he believed the friction rendered the electrified object magnetic.¹ Later studies indicated that friction/rubbing is not a necessary condition to generate charges on contacting surfaces.² We still do not fully understand how and why such charge generation occurs,³,⁴ although considerable progress has been made, such as by considering the role of mechemochemistry⁶,⁷ and the difference of the composite between the surface and the bulk,²,⁴,⁵,⁸ to more closely reveal the CE charging mechanism. Many researchers have suggested that moisture adsorbed on the surface plays a role in CE⁹ and the related ambient humidity is also thought to be particularly important for surface charging.¹⁰ McCarty and Whitesides reported a study on the CE of ionic electrets, in which they elaborated on the role of water in CE and proposed a mechanism based on the theory of the electric double layer to explain charge transfer under ambient environments with different humidity levels.¹¹ Whatever the charging mechanism is, there is considerable evidence suggesting that RH affects the CE.¹²

Much work has investigated the effect of ambient RH once.⁹,¹⁰,¹³–¹⁸ However, existing studies significantly disagree about the effect of RH on CE: some results show that CE increases with increasing RH,⁹ others show that CE decreases as RH is increased,¹⁴–¹⁷ and more still state as RH increases, CE increases at lower RH, followed by decreases at higher RH.¹⁸ In addition, the results of Refs. 19 and 20 show that the dependence of CE on RH is related to the materials properties. However, in their investigation on the effect of RH on CE in gas-solid fluidized beds, Giffin and Mehrani found that the charge or charge-mass ratio did not follow any of the three above-mentioned trends.²¹ Not only is the CE between two materials affected by RH, but also the net surface charges carried on some isolated metals or non-crystals will build up when RH increases.²²,²³

Corresponding authors, e-mail: xieli@lzu.edu.cn, zhoujun@lzu.edu.cn
In general, the natural environment is not completely dry, therefore usually a thin water film or island patch will adhere to solid surfaces of hydrophilic materials. Therefore, it is necessary to investigate the dependence of CE on RH. However, for most existing CE experimental results, the amount of net charge carried on a particle was determined by measuring the charge-to-mass ratio and size distribution of bulk samples of grains in a grain flow. It is difficult to distinguish the role of moisture on the CE. In this paper, we carried out an experiment to observe the CE due to a single collision between two spherical particles in identical materials under different RH, which can identify the effect of RH on CE, and a model is proposed to reveal how and why the contact electrification depends on RH.

II. EXPERIMENTS OF CE UNDER DIFFERENT RH

The instrument used to measure of the CE is detailed in Ref. 26 and is therefore only briefly introduced here. Our experiment is conducted in a glass container with a metal gauze adhered to inside wall to shield external electrostatic fields, as depicted in Fig. 1(a). A Faraday cup is placed at the bottom of the container. A target sphere (sphere 2 in Fig. 1(a)) with radius $R_2$ is fixed in the Faraday cup. An incident sphere (sphere 1 in Fig. 1(a)) with a radius $R_1$ falls from a height $H$ to collide with the target sphere. The relative impact velocity, $v$, can be calculated by $v = \sqrt{2gH}$, in which $g = 9.8 \text{m/s}^2$. The incident sphere will rebound out of the Faraday cup after it collides with the target sphere. The charges carried by the target sphere can be observed as the Faraday cup is connected to an electrometer (Type: Keithley 6517A, USA. Accuracy: 1pC.

![Diagram of experiment setup](image)

**FIG. 1.** (a) Schematic of instrument in the collision experiment to study CE by collision between two spheres; (b) Time series of the net charge of an incident sphere falling into a Faraday cup without colliding with a target sphere, and (c) the time series of the net charge carried by a target sphere with a radius of 10 mm impacted by an incident sphere with a radius of 4 mm, in which the impact speed is 3.96m/s, and the relative humidity and temperature were 46.9% and 294K, respectively.
Range: 0–20 nC). The glass container is filled with pure Nitrogen gas before the experiments. To change the RH in our experiment, we sprayed water vapor into the glass container by a humidifier (Type: YADUSC-M019, China). A thermohygrometer (Type: Testo635-1, Germany. Accuracy: 0.1%, Range: 10%–80%) is used to measure the RH. The spheres used in the experiments are soda-lime glass with radii ranging from 1 mm to 10 mm. The spheres were washed by tap water, distilled water, and alcohol in turn to eliminate any contamination, and were dried for 8 hours before experiments. For each given RH, \( v, R_1 \) and \( R_2 \), 16-24 trials were done.

After the incident sphere is released, it is possible that it becomes electrified due to rubbing with the metal gate and due to rubbing with moist Nitrogen during the free falling process, which is the initial net charge of the incident sphere in our experiment. The initial charges of the incident spheres were measured by letting the incident spheres fall freely into an empty Faraday cup as shown in FIG. 1(b). For comparison, Fig. 1(c) displays the typical result of the net charge carried by a target sphere after a single collision. It can be seen that net charges carried by a target sphere due to a single collision (Fig. 1(c)) are much higher than the initial net charge (Fig. 1(b)) due to rubbing with the metal gate and moist Nitrogen. Therefore, we neglect the effect of the initial charge on collision-induced CE in this paper.

The outliers of raw data were eliminated by the extreme studentized deviate (ESD) test by choosing the significant level 0.05. The change in typical net charges with respect to ambient RH is shown in Fig. 2, in which the relative impact velocity is 3.13 m/s and the radius of the incident and target particles are 5 mm and 10 mm, respectively. From Fig. 2, it can be seen that the amount of net charge carried on the target particle is random at a given RH. However, the mean net charge of target spheres increases with increasing ambient RH when the RH is lower, while at higher ambient RH the mean of net charge of the target spheres decreases as the ambient RH is increased. The mean net charge value reaches a maximum value at the ambient RH in the region (20%, 40%) shown as red circles in Fig. 2, which has the same trend as found by Pence, et al. This increase-then-decrease trend was also observed for different incident and target particle sizes and relative collision velocities, as presented in Figs. 3(a)-3(b). Figs. 3(c)-3(d) shows the change of the standard deviations of the net charge amount of target spheres with respect to ambient RH for the different target particle sizes, particle radius ratio and the relative collision velocity.

### III. MODEL OF CE UNDER VARIOUS RH CONDITIONS

As reported by Harper, many materials are hydrophilic and have thin layers of water molecules on their surfaces. Because of impurities in the insulator, surface states, and defects in the chemical structure, the surfaces of insulators probably consist of some ionic groups, such as a lattice of oxygen atoms. Because of the existence of these ionic groups, an electric double layer comprising

![FIG. 2. Results of net charges carried by a target sphere under different relative humidity, in which the relative impact velocity is 3.13 m/s and the radius of the incident sphere and target sphere are 5 mm and 10 mm, respectively. “○” denotes the measured data and red circle denotes mean values.](image-url)
FIG. 3. Dependence of mean value and standard deviation of net charges carried by target spheres on relative humidity, under different sphere sizes, radius ratios, and relative impact velocities.

a stern layer and a diffuse layer will form on the insulator surface, as shown in Fig. 4(a). When two solid surfaces with electric double layers are brought into contact, the surface electric double layers will also be brought into contact. In Ref. 11, McCarty and Whitesides proposed an experimentally-validated ion transfer mechanism to explain CE for ionic electrets in detail, and they posited that counter ions in the stern layer play an important role in CE.

Here, we proposed a model to explain why counter ions in the stern layer play an important role in CE, and, further, to explain why the dependence of CE on ambient RH is observed differently by different authors, as reported in Refs. 9, 10, and 13–18. In the case of collision contact, the contact force acting on the incident and target sphere contact surfaces could distort the electric double layers. The diffuse layer is liquid-like and is easily forced aside due to collision, while the stern layer sticks to the solid surface firmly. Therefore, the stern layers on the two spheres’ surfaces will be involved in the collision contact process. Including counter ions in the stern layer and original surface patches of spheres, there are two kinds of surface sites brought into contact as shown in Fig. 4(b).

For incident and target spheres of the same material, the surface properties are statistically identical, but the deformations of the two contacting surfaces are different because of the different sizes between both spheres during the collision process. Therefore, the number densities of counter ions bound on the two contacting surfaces show different trends, which may provide the driving force for counter ion transfer between the two contacting surfaces. The counter ions adsorbed on one surface transfer to the other surface, and they can be regarded as donors as reported in Ref. 12. Because the distributions of the counter ions and the original surface patches could be different on the two contact surfaces, the counter ion transfer occurs when one counter-ion site of one surface meets the original sites (named acceptors) on the other surface during the collision. The mean number of counter ions transferred from one contacting surface to the other one can be calculated following Ref. 32; these numbers are not equal because of the differences in the areas that are brought into contact during collision of the two spheres. We refer to the incident sphere and target sphere as sphere 1 and sphere 2, respectively. According to Refs. 32 and 33, the net number of counter ions transferred to sphere 2, $\Delta N$, of the donors between the two surfaces of spheres 1 and 2 can be
calculated by the following expression,

\[ \Delta N = \alpha_{12} N_{D1} \frac{N_{A2}}{N_2} - \alpha_{21} N_{D2} \frac{N_{A1}}{N_1} \]  

(1)

Where \( N_{D1} \) and \( N_{A1} \) are, respectively, the numbers of donors and acceptors on the contacting area of sphere 1, and \( N_{D2} \) and \( N_{A2} \) are, respectively, the number of donors and acceptors on the contacting area of sphere 2. Let \( N_1 \) and \( N_2 \) denote the total number of sites that are possible to give or accept charges on the contacting areas of sphere 1 and 2, respectively, so that \( N_1 = N_{D1} + N_{A1} \) and \( N_2 = N_{D2} + N_{A2} \). \( \alpha_{ij} \), is the probability that a charge will be transferred from surface \( i \) to surface \( j \) \( (i, j = 1, 2) \), which depends on the energy difference between the donors and acceptors, and the ambient temperature. Because the two contacting spheres are of identical material, we assume that \( \alpha_{12} = \alpha_{21} = \alpha \), and \( \alpha = 0.5 \) (see Ref. 32).

Baytekin, et al., pointed out that both the number of donors and acceptors are stochastic variables and obey the binomial distribution.\(^{33}\) Therefore, the number of the net charges from contact surface of sphere 2 to that of sphere 1 is also a stochastic variable, the mean value of which can be obtained by taking the average on both sides of Eq. (1), i.e.

\[ \langle \Delta N \rangle = \alpha \left[ \frac{\langle N_{D1} N_{A2} \rangle}{N_2} - \frac{\langle N_{D2} N_{A1} \rangle}{N_1} \right] \]  

(2)

In which \( \langle \cdot \rangle \) denotes a stochastic average of a random variable. Usually, the number of donors on surface 1 is independent from the number of the acceptors on surface 2. Assume the probability of donors appearing on surface 1 and surface 2 are \( p_{D1} \) and \( p_{D2} \), respectively. Thus, \( \langle N_{D1} N_{A2} \rangle = \langle N_{D1} \rangle \langle N_{A2} \rangle = p_{D1} N_1 (N_2 - p_{D2} N_1) \) and \( \langle N_{D2} N_{A1} \rangle = \langle N_{D2} \rangle \langle N_{A1} \rangle = p_{D2} N_2 (N_1 - p_{D1} N_1) \). According to the two-phase equilibrium model presented by Hogue, et al.,\(^{29}\) the number of counter ions,
i.e. the number of donors, can be calculated by formula (3) as follows,

\[ N_{Di} = \frac{N_i}{(k_B T / \lambda^3) (\Pi / P) \exp (\xi_0 / k_B T) + 1} \quad (i = 1, 2) \]  

(3)

Where \( k_B \) is Boltzmann’s constant (\( k_B = 1.38 \times 10^{-23} \text{ J K}^{-1} \)), and \( T \) denotes the ambient temperature. \( \lambda^3 = [2 \pi m k_B]^{-3/2} \), in which \( m \) is the mass of a charge and \( h \) is Planck’s constant (\( h = 6.63 \times 10^{-34} \text{ J s} \)). \( \Pi = \int_0^\infty \exp \left( -q^2 t^2 / (4 \pi \varepsilon_0 \varepsilon_r k_B T) \right) / t^2 dt \), where \( \varepsilon_0 \) is the thickness of the water film and \( \varepsilon_r \) is the permittivity, and \( q \) is the amount of charges carried on an ion. \( \xi_0 \) is the adsorption energy of the solid surface and \( P \) is the vapor pressure. For a given ambient RH and temperature, the vapor pressure \( P \) can be calculated by the expression \( P = RH \times P_s / 100 \), where \( P_s \) denotes the saturated vapor pressure. Therefore, we have \( \frac{\langle N_{Di} \rangle}{N_i} = \frac{1}{(k_B T / \lambda^3) (\Pi / P) \exp (\xi_0 / k_B T) + 1} \), which means

\[ p_{D1} = p_{D2} = \frac{1}{(k_B T / \lambda^3) (\Pi / P) \exp (\xi_0 / k_B T) + 1} \]  

(4)

Because the two spheres are of identical material, it is assumed that two sphere surfaces have the same number density of sites, \( n \). Therefore, \( N_1 = A_1 n \) and \( N_2 = A_2 n \), in which \( A_1 \) and \( A_2 \) are the collision contact areas of spherical caps on spheres 1 and 2, respectively. Therefore, the mean value of the net number of transferred donors is \( \langle \Delta N \rangle = an p_{D1} (1 - p_{D1}) (A_1 - A_2) \), from which the net charges, \( \langle \Delta Q \rangle \), carried by sphere 2 can be calculated by formula (5), after the collision between spheres 1 and 2,

\[ \langle \Delta Q \rangle = an q p_{D1} (1 - p_{D1}) (A_1 - A_2) \]  

(5)

in which \( p_{D1} \) is given by formula (4) and \( A_1 \) and \( A_2 \) are calculated by the formulas in Ref. 32. Based on (4) and (5), it is obvious that the amount of net charge transferred between the two contacting surfaces is dependent on the ambient RH, temperature \( T \), and adsorption energy \( \xi_0 \). Here, according to the Langmuir isotherm,\(^{30}\) it is assumed that one site can only adsorb one ion carrying one elementary charge, i.e. \( q = 1.6 \times 10^{-19} \text{ C} \). Lee and Pantano found there were 7.2 dangling bonds per nm\(^2\) on the fracture surface of glass.\(^ {35}\) Because dangling bonds may form donors or acceptors, we assume the number density \( n \) in (5) be of the same order as that of dangling bonds, i.e. \( n = 1.0 \times 10^{19} \text{ m}^{-2} \). And \( z_0 \) is taken as 3.2 \( \times 10^{-8} \) m, which is the effective van der Waals diameter of one hundred water molecules, as reported in Ref. 29. With the above-mentioned parameters given, the amount of net charge transferred between the two contact spheres can be calculated for different ambient RH and temperature. Fig. 5 shows the dependence on RH for the net charge amount due to collision, compared with the results given by the proposed model (i.e. the formula (5)) in this paper, in which \( R_1 = 5 \text{ mm}, R_0 = 10 \text{ mm}, \) and \( v = 3.13 \text{ m/s} \). It can be seen that the CE depends on the ambient RH and the absorption energy of the surface. For lower absorption energy, the amount

![FIG. 5. Dependence of net charges of CE due to collision on ambient RH, which are compared with the results given by the proposed model, i.e. formula (5). Here, hydrogen ions, \( \text{H}^+ \), mass of \( 1.67 \times 10^{-27} \text{ kg} \), are assumed to be the charge carriers that are transferred between the two contacting surfaces.](image-url)
of net charge arising from collision increases with increasing RH at lower RH ranges and decreases as RH increases at relatively higher RH ranges, which agrees with our experimental results and the results observed by Pence, et al.\textsuperscript{18} Based on the proposed model, it is found in Fig. 5 that for higher absorption energy the amount of net charges due to collision decrease with increasing RH, which agrees with the results in Refs. 14–17.

Examining formula (5), and it can be found that the amount of net charge transferred between two contact surfaces is a quadratic function of the probability \(p_{D1}\) of donors on the surface, which is dependent on ambient RH, temperature \(T\), and the adsorption energy \(\xi_0\). Therefore, for a given \(\xi_0\) and temperature \(T\), if \(p_{D1}\) lies in \([0, 0.5]\) with increasing the ambient RH, the amount of CE monotonically increases with ambient RH. If \(p_{D1}\) lies in \([0.5, 1]\), ambient RH conditions, CE monotonically decreases with ambient RH; otherwise, if \(p_{D1}\) goes through 0.5 with increasing ambient RH, CE would be a function of RH with a maximum.

IV. CONCLUSIONS

In conclusions, we investigated the ambient RH dependence of CE by conducting collision experiments between two glass spheres, and proposed a model for predicting the amount of net charge due to collision, which is capable of predicting three kinds of existing experiment results regarding the dependence of CE on ambient RH. The proposed model can yield results that are in agreement with those of our experiments. The proposed model is achieved by taking the probability \(p_{D1}\) of donors on a solid surface, which is covered with an electric double layer, as a function of ambient RH, temperature \(T\), and the adsorption energy \(\xi_0\). In addition, it is worthy of pointing out that in our calculation we used H\(^+\) as donors because Pence, et al. H\(^+\) is important for CE under water surface,\textsuperscript{18} which need further study to valid it.

ACKNOWLEDGEMENTS

This research is supported by Innovative Research Group of the National Natural Science Foundation of China (No. 11421062) and by key grant of the National Natural Science Foundations of China (No. 51435008) and by grants of the National Natural Science Foundations of China (Nos.11472122, 11272139). The authors would like to express their sincere appreciation of this support.

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