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The analysis of electrification in windblown sand

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ABSTRACT

Based on asymmetric contact, we present a contact electrification model of high-energy trapped holes which considered the plastic deformation of the contact process in a single normal collision to predict the contact electrification and the charge-to-mass ratio of sand particles. Furthermore, the contact electrification was measured using a charge collection method. Our results show that the charged species trapped in high-energy states of sand particles are positive holes, the predicted results agree well with our experiments qualitatively and quantitatively, the impacting velocity and the particle size are two important factors affecting the magnitude of the charge-to-mass ratio of sand particles, and the number of collisions also affects the charge-to-mass ratio of sand particles.

1. Introduction

In natural and industrial granular flows, the existence of electrostatic charges has been widely acknowledged (Gill, 1948; Ciborowski and Wlodarski, 1962; Yao et al., 2004; Mather and Harrison, 2006) and become an increasingly active area of research in recent years. Compared with the electrostatics in fluidized-bed or other industrial processes, the electrification of natural granular systems such as wind-blown sand flows (Gill, 1948; Freier, 1960; Schmidt et al., 1998), snowstorms (Gordon and Taylor, 2009), volcanic plumes (Miura et al., 2002; Mather and Harrison, 2006) etc. are more complicated due to wider ranges of spatial scales, more complex surface conditions, and diversity of particle size and geometric shape involved in these phenomena. The existence of electrostatic charges have great effect on the flashover and breakdown of transmission lines, electromagnetic wave propagation etc. Similarly, electrified ash plumes over erupting volcanoes have been known to generate lightning which could pose a risk to air traffic (Farrell et al., 2003). On other planets, such as the Mars, the electrification of wind-blown sand and dust storms could also affect Mars exploration. Therefore it is necessary to make in-depth investigations on the mechanism of the electrification of wind-blown sand so as to effectively prevent its damage.

In wind-blown granular systems, such as sand/dust storm, wind-blown saltation, and dust devil, the statistical average of charge polarity is found to be dependent on the particle size, i.e., the larger/smaller particles tend to be positively/negatively charged (Freier, 1960). Other scientists also confirmed his result (Greeley and Leach, 1978; Zheng et al., 2003; Kok and Renno, 2008; Forward et al., 2009). It should be noted that the conclusion about the charge polarity is a statistic-based meaning, and the charge-to-mass ratio used to characterize the charges of sand particles is the average charges per unit mass. Generally, the charge-to-mass ratio can be obtained by measuring the total charges and mass during a certain period of time. Sand particles are collected by a faraday cage (cup) or other similar equipments, so that the total charges and mass of the collected particles can be measured by an electrometer and a balance, respectively (Kamra, 1972; Schmidt et al., 1998; Fuerstenau and Wilson, 2004; Kok and Renno, 2008). Table 1 lists recent experimental results of charge-to-mass ratios which vary in a wide range. In addition, it also implies that particle size and wind velocity have obvious influence on the charge-to-mass ratio. In general, smaller particles get larger charge-to-mass ratios, for example, it can be up to 10 C/kg for particles of 0.4–50 μm (Fuerstenau and Wilson, 2004). It is because smaller particles have smaller mass though the charges are equal during charge transfer between large and small particles in wind-blown sand flows. Moreover, experimental results demonstrate that the charge-to-mass ratio increases with wind-velocity at the same height, but decreases with height at the same velocity (Zheng et al., 2003). It can be explained by the decreasing of the average grain size and concentration with height at the same velocity and their increasing with wind velocity at the same height. Certainly, above explanations are also base on a fundamental law

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Table 1
The experimental results of charge-to-mass ratios in wind-blown sand flux.

Reference	Charge-to-mass ratio (μC kg^{-1})	Diameter (μm)	Wind velocity (Height) (m s^{-1})
Schmidt et al. (1998)	66	250	7 (1.5 m)
Sickafoose et al. (2001)	10^2–10^4	100	–
Gross et al. (2001)	10^2–10^4	100	–
Zheng et al. (2003)	−124–0.95	0–1000	7–20 (0.45 m)
Qu et al. (2004)	−304–158	80–315	8–22 (0.3 m)
Zhang et al. (2004)	−24.3–65.8	100–600	8–22 (0.3 m)
Fuerstenau and Wilson (2004)	-3.5×10^7–3.8×10^7	0.4–50	–
Merrison et al. (2012)	10^4–10^6	1	1–25
Merrison (2012)	10^4–10^6	1	1–25

of physics, i.e., when large and small particles contact and separate, the generated charges are the same in magnitude but opposite in polarity (Freier, 1960; Latham, 1964; Zheng et al., 2003; Zheng, 2009).

The contact electrification in a single collision event is fundamental to understand the electrification phenomena in granular systems, e.g., sand-bed collision and mid-air collision events in wind-blown granular systems. Although statistical averages of charge polarity and charge-to-mass ratio are observed in granular systems, factors affecting the magnitude and polarity of contact electrification on particle–particle collisions have not been considered. Poppe et al. (2000) carried out the early experiments about the contact electrification considering a micron or submicron silica particle impacting a similar or identical insulator plane, and found that the magnitude of contact electrification is related to the impact energy and most particles are negatively charged. Due to the difficulty of directly and precisely measuring the electrification of sand particles, the contact electrification mechanism still stayat speculations and hypothesis stage which can be generally divided into seven classes (Kanagy and Mann, 1994). Here, the most possible mechanisms are the tribo-electrification and the contact electrification. It should be noted that friction and collision are two different kinds of contact types between sand particles' surfaces (Awad et al., 2002). For friction, the frictional distance affects the electric charges more than the friction velocity (Lowell and Truscott, 1986a,b). Lowell and Rose-Innes (1980) pointed out that rubbing is not necessary and mere contact is sufficient to cause the transfer of considerable charge. Therefore, the tribo-electrification and the contact electrification together are thought to be the contact electrification mechanism of sandparticles' electrification, which have attracted more and more scholars' interests (Lacks and Levandovsky, 2007; Shinbrot and Herrmann, 2008; Kok and Lacks, 2009; Zheng, 2009).

For the contact electrification mechanism, there are two kinds of contact electrification models to depict the electrification of sand particles, i.e., the asymmetric contact electrification model and the contact potential difference model. The former is established on the work function theory (Randall and Wilkins, 1945; Kok and Renno, 2008), for instance, Kok and Renno (2008) proposed an effective contact potential difference between pairs of similar composition but different sizes, and explained why larger particles positively charge and smaller particles negatively charge. The latter is based on the high-energy trapped charged species theory (Lowell and Truscott, 1986b) with assumption that there are two surface states in the insulator surfaces, i.e., high-energy and low-energy states. Charged species may be trapped in high-energy states, when contacting with another surface they can relax to low-energy states on the other surface; after the species relax to low-energy states. Lowell and Truscott (1986b) pointed out that the charged species are electrons, and the electrons trapped in high-energy states remain there for periods of days to centuries verified by phosphorescence and thermo-luminescence measurements (Randall and Wilkins, 1945). Except for electrons (Lacks and Levandovsky, 2007; Kok and Lacks, 2009; Hu et al., 2012), the charged species can be generalized to be ions (positive or negative) (Castle, 2008; Pham et al., 2011) and holes. Noteworthy, quite a few scholars have adopted the asymmetric contact electrification model to explain the electrification and charge transfer of sand and other insulating particles (Lacks and Levandovsky, 2007; Castle, 2008; Forward et al., 2009; Kok and Lacks, 2009; Pham et al., 2011). Kok and Lacks (2009) deemed the charged species as electrons and proposed a charging scheme for granular systems of identical insulators. Assuming the initial densities of high-energy trapped surface states of particle i and j are both equal to ρ_H, the number of the high-energy states trapped electrons tunneling from particle i to j is $\pi\rho_{\mathrm{H}}e\delta_0R_i(2R_j+\delta_0)/(R_i+R_j)$, where δ_0 is the tunneling distance and e is the elementary charge. After particle i and j separate, the net charge transfer of particle i is $\Delta q_i = \rho_{\mathrm{H}}\pi e\delta_0^2(R_i-R_j)/(R_i+R_j)$. Therefore, when $R_i < R_j$, $\Delta q_i < 0$ which can explain why "larger particle tends to be positively charged and smaller particles tends to be negatively charged". However, these contact electrification model did not be validated by experiments.

In this study, we presented a high-energy trapped holes (HETHs) contact electrification model which considered the plastic deformation in the contact process to predict the charge-to-mass ratio (CMR) of sand particle based on asymmetric contact. The charged species trapped in high-energy states can be positive holes, which help us to understand the tribo-charging phenomena of sand particles in a more clear way. Furthermore, we carried out experiments of charge-to-mass ratios of particles with normal glassy particle-glassy particle-steel plate, to check the validation of the model. In addition, the influence of the number of collisions on the charge-to-mass ratios of sand particles was investigated.

2. Experiment

In sand and dust granular systems on earth and Mars, SiO_2 is the primary chemical composition. Therefore, glassy particles were used in the normal collision experiments. Glassy particles are standard spherical particles manufactured by Li Ning Glass Co., Ltd., whose radius ranges from 1 to 10 mm. In a single normal collision, the impacting particle falls at height h then rebounds from the faraday cup, the net charges transferred from the impacting glassy particle to the impacted glassy particle q_2 are measured by an electrometer (Keithley 6517A, measurement range is 2 nC, resolution is 10 fC), as shown in Fig. 1, where the impacting velocities are calculated by exerting the aerodynamic drag and gravitational forces (Zheng et al., 2003; Kok and Renno, 2008). The information of mechanical properties of glassy particles is supplied by the manufacturer, for example, the Young's modulus, the Poisson ratio, and the compressive strength of the employed glassy particles are 60 Gpa, 0.3 and 320 ± 20 Mpa, respectively. For the steel, the Young's modulus, the Poisson ratio, and the compressive strength are 210 Gpa, 0.3 and 400 Mpa, respectively (Field and Swain, 1993; Paik et al., 2003). The setup is in an airtight container filled with nitrogen to avoid the air moisture. Since the pre-charging of particles (about 10^{-6} nC/kg) is far less than the experimental results, experimental data did not do verification, i.e., theinfluence of the pre-charging of particles was neglected.

In order to facilitate the experimental operation, radius of particles are taken as millimeters (from 1 to 10 mm, the interval is 1 mm). It should be noted that we use 'sand' as a broad description