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Numerical simulation of particle size effects on contact electrification in granular systems

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ABSTRACT

Based on the contact charge transfer model between two particles due to a single collision proposed by Apodaca, the contact charges carried on a particle is derived due to multiple collisions, including the repeat collisions between two particles and the collisions with different particles, in mixed-size granular system of identical material. The effect of the particle size on the charges carried on the particle is simulated. The results indicate that for a mixed-size granular system, due to multiple collisions among particles, there exists a threshold particle radius, the particles with radius higher than which and the particles with radius lower than which carry opposite charges. The threshold particle radius is equal to mean value of particle size in the mixed-size granular system. Basically, the polarity of the charges carried on the largest particle is same as the polarity of the transfer charge carrier, and in case of the positive charge transferred, the largest particle will be positively charged and the smallest particle will be negatively charged, and vice versa. In the same size region, the more dispersive the particle size is, the more the net charges can be produced. In normal-distributed granular system, the magnitude of contact charge is determined mainly by the particle size distribution, size region, total particle number and the relative impact velocity.

1. Introduction

When two surfaces are brought into contact, they will generally exchange charge and when subsequently separated will be oppositely charged [1]. This phenomenon is called contact electrification, which can be commonly observed in granular system in our daily life, such as electrostatic painting and electrostatic hazards control [2]. Electrostatic is not only important in controlling pollutions, such as electrostatic precipitators, but also greatly improved the technologies of electrostatic copying (xerography) and spray-painting [3]. However, it may be a nuisance in industry, where sparks generated by static electrification may cause explosions such as in mining [3].

Particles in granular system especially in the natural granular system are not equal in size, such as that the distribution of dust particles on Mars is gamma distribution [4], however, under the strong wind, the size of the particles about 50 μm in diameter away from the Mars surface obeys normal distribution [5]. Many works indicated that the size of particles obeys logarithm distribution in the sand particle system [6–9], and the size region and the average particle size are different in different deserts.

Experiment results of the previous studies showed that the sand particles larger than 500 μm in diameter carry positive charges, while the sand particles smaller than 250 μm in diameter carry the negative charges [10]. That means the sand particles with diameter between 250 μm and 500 μm may carry either positive charges or negative charges, the threshold diameter is between 250 μm and 500 μm. However, Greeley and Leach showed that the threshold diameter is 60 μm [11], when particles with the diameter higher than 60 μm carry positive charges, while the particles with the diameter lower than 60 μm carry negative charges. In addition, the Aeolian electric field formed by the charged sand particles in mixed size is much stronger than that formed by the charged sand particles in single size [10,12]. Furthermore, in the experiment of electrostatic discharging of dust near the surface of Mars, it was also found that the significant discharges rates occurs only when there is a mixture of particle sizes [13].

There are also many works in the literature on modeling the effect of particles sizes on electrostatic charge [14–18], regardless of the particle charging mechanism under consideration, the conclusion is usually that larger particles become positively charged and smaller particles become negatively charged. There are two typical works reported by Lacks et al. [19,20] and by Konopka et al. [21]. In Refs. [19,20], based on the electron trapped in high-energy states, they

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simulated the triboelectric charging occurred in granular insulating system. By comparing charge on particles produced in monodispersal system, bidispersal system and polydispersal system, it shows that the magnitude of charging is much greater in polydispersal system. In Ref. [21], based on the transfer of negative species during collision, they utilized DEM method to simulate a powder system charging process, especially described the charging on specific spherical particle, which make a step towards previous study. In order to investigate how particle size influence the electrostatic charging, they changed the size region in a uniform mass particle size distributed system, and concluded that charging is more pronounced in wider size region.

Even though that the wider the size region is, the greater the charge produced is widely accepted in most simulation and experimental results, it is still not clear how the particle size distribution actually affects the charge carried on the particles in mixed-size granular systems. There are some common forms in natural granular system, such as normal distribution, log normal distribution, exponential distribution, and uniform distribution. Motivated by this, we derived the charges carried on a particle due to multiple collisions with multiple particles in a mixed-size granular system in section II, and then the evolution of the charges on each particle is simulated in section III, and finally results, discussions and the conclusions are drawn in sections IV and V.

2. Numerical simulation of contact electrification due to multiple collisions

Assume a mixed-size granular system composed of N sphere particles with the same material, radius distribution of which is $p(R)$, as shown in Fig. 1(a). During the transportation, there are many collisions can happen, such as the repeat collisions between two particles and the multi-collisions among many particles. As the collision-electrification model proposed by Apodaca [22], the particle will be electrified due to a single collision with other particles, based on which, next we will deduce the charges carried on a particle due to multi-collision with many other particles in a mixed-size granular system.

Assume a particle i and a particle j collide with each other. The collision probability of the particle i with the particle j is assumed as $C_{i,j}$, which is determined by the particle number in the granular system and the particle size distribution. As detailed in Ref. [20], the collision probability is proportional to the product of this swept out volume and the number densities of particles with radius R_j, which is $(R_i + R_j)^2 p(R_j)/\sum_{q=1}^{M}[(R_i + R_q)^2 p(R_q)]$ (M is the number of distinct particle sizes), in which, the probability of the particle with the radius R_i is $p(R_i)$, and the probability of the particle with the radius R_j is $p(R_j)$. Therefore the collision probability between the particles i and j is $C_{i,j} = (R_i + R_j)^2/\sum_{q=1}^{M}[(R_i + R_q)^2 p(R_q)]/N^2 p(R_i)$ by considering $Np(R_j)$ particles with same radius R_j have an equal probability colliding with the particle i.

Assume that particle i first collide with particle k ($k = 1, 2, \ldots, N$, $k \neq i$) to see Fig. 1(b)–(d). Before colliding with particle j, particle i has encountering $(n-1)$ collisions and $(m_j - 1)$ collisions for particle j. Here, we consider the particles are randomly covered with only two types of charge sites following Apodaca's idea [22], named as donor and acceptor. The distribution of donors and acceptors after the nth collision between particle i and particle j is as shown in Fig. 1(e). It is clear that a collision between any two particles only occurs within a very limited particle surface, and not the whole particle surface. Therefore, a single collision only changes the distribution of the charge site, such as donor, in a very limited area, as shown in Fig. 1(c). The number of donors on the particle changes after each collision. However, when multiple collisions occur between particles, or a given particle collides with all other particles, the collision contact surface will be randomly distributed over the particle surface. Consequently, it becomes very difficult to determine the donor distribution. In this paper, for simplicity, we assume that the donors are evenly redistributed after each collision and the probability of donor is the same anywhere on the entire surface of the particle.

Next we provide a detailed analysis of this behavior. For particles i and k before the first collision, the distributions of donors and acceptors are as shown in Fig. 1(b). Because we assumed that all particles are consisted of the same material, the distributions probability of the donors on the two particles are the same as shown in I and II in Fig. 1(b).

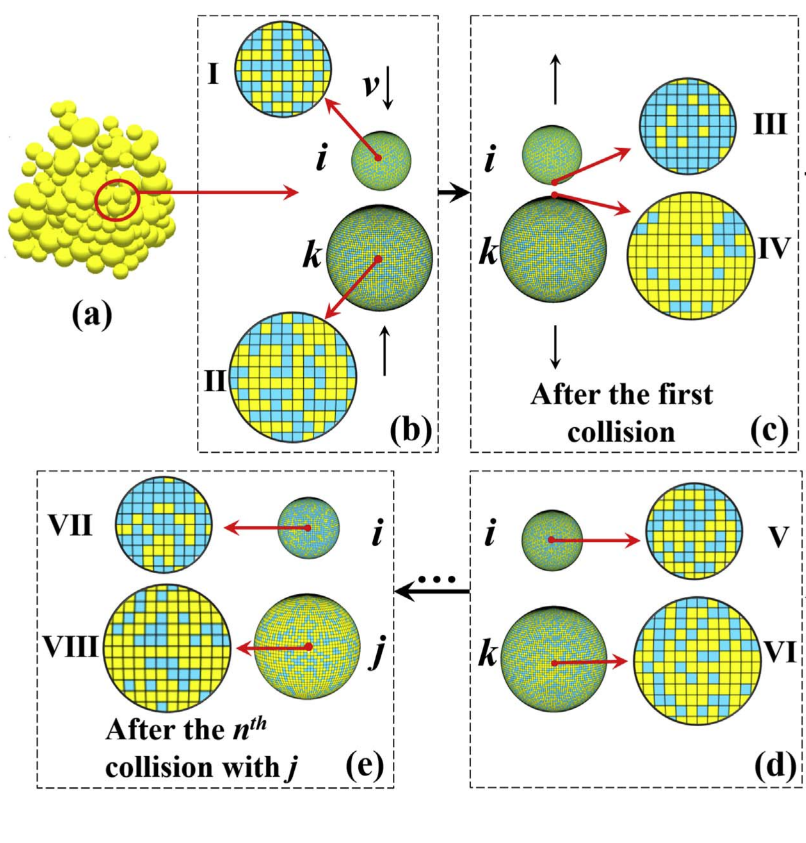

Fig. 1. Schematically illustration of Mosaic model on particle surface during collision. (a) A granular system with N particles under certain size distribution. (b) Before the particle i collides with particle k ($k = 1, 2, 3, \ldots, N$, $k \neq i$) with velocity v, $R_k > R_i$. The distributions of the donors on two particle surfaces are same because of same particle materials. I and II are the magnified distributed pattern of donors on particles i and k. (c) After the first collision, the donors are transferred between two contact surfaces, due to the difference between particle sizes, and the number of donors transferred to and from each particle will not be equal, which causes the donor distributions on the contact surfaces of two particles are not same, such as that V is the donor distribution on the contact surface of particle i and VI is the donor distribution on the contact surface of particle k. For the same particle, the donor distribution on the contact surface is different from that on the uncontact surface, like V and III for particle i, and VI and IV for particle k. (d) After the first collision, the donors on each particle, i and k, redistribute over the particle surface and make the distributions of donors on the contact surface and the uncontact surface same. VII and VIII are the magnified donors distribute pattern on particle i and k after the redistribution of donors. (e) After the n^{th} collision, the distributions of the donors on particle i and particle j.