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Experimental and modeling study on mechanisms of sliding and rolling electrification

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ABSTRACT

Triboelectrification due to frictional contact between particle and wall is prevalent in gas-solid systems. However, mechanisms of triboelectrification are not fully understood, such as the difference in the charge generation between the sliding and rolling contact. In this study, a dynamic model for the sliding and rolling electrification was developed based on the continuous condenser model. Results show that the triboelectric charge of the cylinder rolling on its round surface is larger than that of the cylinder sliding on its bottom base. Also, we proposed the triboelectric coefficient to characterize the tribocharging process. The triboelectric coefficient was an essential characteristic involved the re-charging process and the discharging process. The rolling electrification of the sphere shows a smaller triboelectric coefficient than that of the sliding electrification due to the small contact area. To shed light on the vital significance of the triboelectric coefficient, we define a dimensionless triboelectric charge to area ratio to represent the ratio of the incremental charge to the maximum triboelectric charge.

1. Introduction

Triboelectrification is unavoidable in particulate operations during sieving, mixing, pneumatic transport, and gas-solid fluidization [1–3], etc. Nuisance charge build-up may significantly affect the hydrodynamics of particles and result in agglomeration, particle–wall adhesion or segregation [4–5]. Particle-particle and particle-wall contacts are the basic mechanisms behind the electrostatic charge of particles. Thus, interactions between particles and the vessel wall have been considered as the primary source for particle charging [5].

Many scholars have studied the charge generation via colliding single particles with plane surfaces [6–8]. For instance, Matsusaka et al. [6] found the impact charge was a function of the contact area and the impact speed during single particle-surface impacts. Matsusyama and Yamamoto proposed a charge relaxation model for the impact charging, in which the separating process was more important than the contacting one [7]. The contact electrification was frequently represented as a condenser model [4,7,9], where the electrification efficiency of contact charging, the contact potential difference, and the contact area governed the charge transfer.

In recent years, some researchers have modeled the process of static charging in powder handling systems. Pei et al. [4,10] analyzed the charge transfer and electrostatic interactions in a 2D fluidized bed employing the DEM-CFD method. A similar simulation on the tribocharging distribution of granular plastics in vertically-vibrated beds was conducted by Laurentie et al. [11] based on the condenser charging model. Naik et al. [12] and Mukherjee et al. [13] used the triboelectric charging model described by Laurentie, et al. [11] to simulate the tribocharging progress of pharmaceutical excipients flowing on a chute surface. On the other hand, Hogue et al. [14], Cheng et al. [15], and Kolehmainen et al. [16] simulated the electrostatic charge generation under the hypothesis of the triboelectric charge was a function of the contact time [17]. However, all the models above for predicting particle charging are by the assumption of the interactions between particles and the wall surface are continuous collisions.

It is inappropriate to hypothesize contact modes of particles as only collisions in some real systems. For example, in the cases of cyclone tribochargers, inclined plate surfaces or the dense phase pneumatic conveying lines, frictional contacts involved sliding, or rolling contacts will be the primary contact process between particles and wall rather than collisions [18–19].

There is extensive evidence that the frictional electrification is more complicated than the contact electrification [20–28]. The age-old argument is which factor determinates the triboelectrification transferred more charge compared with the contact electrification. Ireland [20] and Hu et al. [21] stated that the frictional electrification yielded more charges than the contact electrification did due to the more contact area in the frictional contact. Furthermore, the asymmetry of rubbing between grain and plate might cause a temperature increase, which induced charge transfer [22]. A recent experiment stated the rubbing heating correlated with the electric potential at the charged surfaces which was reflected by the thermal field distribution [23]. Zhou et al. [24] quantitatively compared the contact electrification and

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triboelectrification at the nanoscale based on scanning probe microscopic methods with the same contact time and force. They suggested the energy dissipation at the frictional interfaces hastened the charge exchange via electronic excitation. Apart from the frictional heating, sliding can produce more surface damage and material transfer than simple contact [25]. Based on analytical electron microscopy coupled with electrostatic potential mapping techniques, Beraldo et al. [26] reported that mass transfer between the surfaces caused by the rubbing played an essential role in triboelectrification. Baytekin et al. [27] and Williams [28] found the rubbed products were concurrent to the triboelectrification.

Additionally, some results suggested the stress of rubbing played roles in the charge generation [21,23,29–31]. Son et al. [29] found the rubbing stress generated electron-hole pairs near the Fermi level, which resulted in electrostatic charge generation. Based on a Kelvin probe force microscopy-based method, Sun et al. [32] found the polarity of triboelectric charge reversed by varying the loaded forces between tips and substrates. Also, tribocharging variations due to different contact modes of sliding contact and rolling contact have been studied in some detail [18,33,34]. Many researchers suggested the smaller real contact area was responsible for the low electrostatic charge gained by rolling electrification compared with the sliding electrification.

Given these complicacies in the frictional electrification, one would wonder that how these particular factors affect the charge exchange in the simple normal contact, in the sliding process or the rolling process? Alternatively, in what specific manner do these factors work on the charge generation? There are some attempts to describe the physical model for the charging progress in the light of the characteristics in triboelectric charging. Ireland [20] proposed that the sliding could provide a cumulative surface area by changing the contact pattern. Considering the work of sliding friction at the interface, Ireland [19] added a frictional charging term in the capacitive contact model to describe dynamic particle-surface tribocharging. In our recently published paper, a continuous contact-separation process was employed to model the sliding contact [21]. The triboelectric charge to area ratio increased with the sliding distance. Moreover, the triboelectric coefficient was found to vary in different sliding distance. Ema [35] introduced a rolling-slipping model to analysis the triboelectricity. The rolling-slipping was different from the perfect rolling by considering the average rolling speed.

In this paper, we use a new method to measure the initial charge and the triboelectric charge in the triboelectrification. Besides, we clarified the triboelectrification in the perspective of the triboelectric coefficient based on the continuous condenser model. The inherent difference between the sliding electrification and the rolling electrification was illuminated via the triboelectric coefficient. Moreover, the vital significance of the triboelectric coefficient was represented by a dimensionless parameter.

2. Materials and experimental systems

2.1. Test grains

Fig. 1 shows the grains used in the study: cylindrical grains and spherical grains for the sliding electrification test and the rolling electrification test, respectively. For easy identification, we named cylindrical grains and spherical grains alternatively. For instance, the cylindrical POM grain was named POMC, and the spherical POM grain was named POMS. Table 1 provides details of test grains. Each columnar grain had a plane bottom base which was chosen to be the sliding surface to guarantee the sample slides smoothly on the plate. POM grains and HDPE grains were polymers from AHD Plastic Group, China, while Cellulose grains were tableted from cellulose powders provided by Sunhere Pharmaceutical Excipients Co., China.

POMC #1 and POMC #2 had the same diameter but different heights to provide a different normal load on the sliding surface. Meanwhile, we used three different sizes of POM spheres in the test, where all spheres had an average sphericity of 0.95.

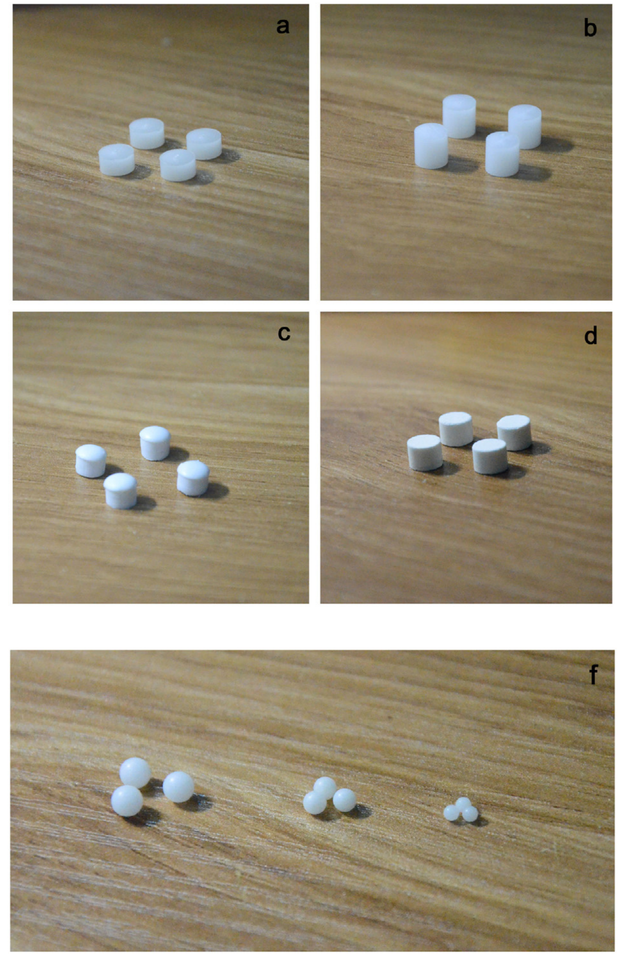

Fig. 1. Pictures of test grains: POMC #1(a), POMC #2(b), HDPEC(c), CelluloseC(d), and POMS(f).

To ensure the sample surfaces was uncontaminated, we soaked test grains in alcohol for 30 min and rinsed them with deionized water five times. Then, these grains were dried at 50 °C over 12 h in a drying oven (DHG-9070A, China).

2.2. Experimental systems

Fig. 2 shows the schematic diagram of the experimental apparatus. The sliding electrification test was conducted in a Plexiglas glove-box, which was protected by nitrogen from the moist atmosphere. We used a humidity and temperature transmitter (Vaisla HMT330, Finland) to monitor the humidity and temperature in the box, controlling the relative humidity and temperature in the test at $5 \pm 1\%$ and 20 ± 2 °C.

A throughout-type Faraday Cup was mounted in the box relative to the horizontal level at 35°. Fig. 2 displays an inclined PVC plate lay through the inner cup of the throughout-type Faraday Cup without touching the wall of the inner cup. The inner cup had a diameter of 55 mm and a length of 200 mm, and the plate was 40 mm wide and 250 mm length. The effective frictional length was deemed to be the length of the inner cup, i.e.,200 mm. The grounded outer cup was well insulated with the inner cup. An electrometer (Keithley Model 6514, USA) connected to the inner cup with a coaxial cable.

In each test, the single grain was picked by a bamboo clip onto the front of the plate near the opening of the throughout-type Faraday Cup. Then the sample grain passed through the throughout-type