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Investigation of granular surface roughness effect on electrostatic charge generation

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ABSTRACT

Electrostatic charge generation is a multivariable and complex issue whose working mechanism has never been fully understood. The objective of this paper is to investigate the effect of granule surface roughness on electrostatic charge generation. Two kinds of granule material, Polyvinyl chloride (PVC) and polypropylene (PP) were used with the granule size of 4 mm diameter, 2 mm height and the shape was cylinder or semi-cylinder. The working surfaces were grounded and roughness ranged from 0.140 to 8.600 μm. It was found that uneven surfaces tended to give rise to voids between two solids, where air stored in the voids was able to accelerate discharging. With the same roughness, PVC tended to generate more electrostatic charge than PP by one order of magnitude. For both materials, electrostatic charge generation first increased with surface roughness and then decreased. The maximum electrostatic charge generated was found to occur when the effects of interaction, contact area and voids discharging were at equilibrium. With the combined effect of humidity, surface roughness and contact area, highest electrostatics generation occurred near the mid-roughness tested in this work. Humidity had more effect on electrostatic charge generation as the granule working surface had lower roughness.

1. Introduction

In solid-handling industries, electrostatic charges are generated due to granule-wall and granule-granule contacts with different potentials. On one hand, electrostatic charges generated cause lots of problems such as granule agglomerating, adhering to the vessel wall and ultimately leading to unstable fluidized beds [1]. Electrostatic charges are continuously generated and accumulated in the working system. As the amount of electrostatics reaches the saturated state, significant amount of electrostatics can suddenly discharge and may lead to spark, fire or explosion. On the other hand, electrostatic charge generation can be applied in emerging particle processing techniques such as electrostatic precipitation [2], electrohydrodynamic atomization (EHDA) [3], and electrostatic coating [4]. Although triboelectricity phenomenon has been known for a long time, the working mechanism has not been fully understood. Particularly, surface roughness effect on electrostatic charge generation has not been fully investigated due to its complexity. This study aims to investigate the surface roughness in combination with other elements affecting electrostatic charge generation.

The mechanism of electrostatic generation has been explored for a long time. One of the early models proposed is the condenser model [5], which considers charge relaxation with elapsed time in a repeated impact process. Based on one impact, Matsuyama [6] set up a so-called charge relaxation model. It says that the distance between the granule and the wall increases with the contact surfaces apart from each other, while the capacitance decreases if the charges remained constant. The voltage rises until it reaches the level of the gas breakdown causing discharging phenomenon. The final charge left is called "residual charge". As a complement [6] to the condenser model [5], the non-quantitative defects of the condenser model were recovered. Ireland [7] studied the charge accumulation and separation of the discharging process and found that the discharging phenomenon had a significant influence on the accumulation of charge by numerous contacts. In order to avoid possible accident arising from discharging, it is important to control this phenomenon. Discharging could be eliminated by imposing high charge separation through adding an applied deflection voltage to the proof-plane. The changes caused

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by combinations of conductors and insulators were studied, for example, surface-state model [8] and molecular ion state model [9].

In addition, the effects on electrostatic charge generation also have been investigated in the literature. Masuda et al. [10] studied the effect on the electrostatic potential, where propylene - styrene acryl particles were used to prove that the potential of the particles is proportional to the square of layer thickness. Guardiola et al. [11] studied the effect of the relative humidity (RH) on the electrostatic charge of glass beads in a fluidized bed and confirmed that when the RH was less than a certain value, electrostatics was low, unstable and independent of RH. The amount of charge is kept approximately constant with moderate increase in RH while further increase beyond RH_{max} results in instantaneous discharge and no electrostatics charge is retained anymore. Mehrani et al. [12] used a Faraday cage to perform on-line testing on electrostatic charge of particles as particles were transported in a fluidized bed and demonstrated that the variation caused by the surrounding air could be ignored and the charges mainly arose from particle-wall interaction in the fluidized bed. In addition, due to particle attrition or breakage in industrial solid-handling systems, particle size and shape become variable in the process. Yao et al. [13] studied the effect of granule size and shape on electrostatic charge generation in pneumatic conveying systems and found that the amount of charge generated was correlated with the contact surface shape and area. Furthermore, three typical flow patterns due to electrostatics were observed over three ranges of flow rates by Yao et al. [14] in a pneumatic conveying system. From the analysis on the equivalent current, charge density and maximum charge, they confirmed that the electrostatic change generated increased with time until the saturated state was reached and specific flow patterns were formed. Recently, Yao et al. [15] studied the normal stress effect on electrostatic charge generation in combination with the humidity, saturation and contact area for single granule sliding along a metal plate. It is found that normal stress is a significant factor effect on the contact area of granule-metal plate to determine charge generation. Jiang et al. [16] studied the wall surface roughness effect on granule flow patterns where particles flew away from the wall after a short slide and very few particle-particle collisions occurred at the submicron scale. They found that the entrainment air velocity decreases with the increase of surface roughness within the submicron-scale, and becomes smallest at $Ra \approx 0.3$. Micron-scale surface roughness, however, does not effectively reduce the interaction force due to the geometrical effect.

With the advances in computation resources, more and more researchers have integrated electrostatics effects into simulations of particle tracking. Hogue et al. [17] applied discrete element modeling (DEM) to investigate the trajectories of charged particles with consideration of electrophoresis and van der Waals forces to obtain a more accurate charge generation constant and charge to mass ratio. Lim et al. [18] applied the methodology of coupling large eddy simulation (LES) with the discrete element method to investigate the electrostatic effect on granular material transportation in pneumatic conveying systems. They found that the electrostatic effects became a dominant role in influencing granule behaviors in pneumatic conveying at low flow rates, whereas drag force was important at high flow rates.

Subjects of granular electrostatics studied include mass of granules as a group [13,14,18] and single granules [15,19]. In granular pneumatic conveying systems, three typical granule flow patterns were found [14] and related electrostatics working mechanisms were studied [19]. In pneumatic conveying systems, granules were broken or attrited due to granule-wall or granule-machine-component interactions and smaller granules were generated [20]. Effects of granule size and shape on electrostatics charge generation were investigated [13]. To get in-depth understanding of the electrostatics of grouped granules, electrostatics of single granule was first studied [15,19]. The effects of normal stress in combination with process parameters such as humidity, saturation and contacting area on electrostatics generation were studied [15]. Furthermore, granular shape parameters including front-facing angle, length-ratio, in-touch area, sliding orientation as well as sliding times, and relative humidity were studied for their effects on the electrostatics generation [19]. However, so far, little has been found to investigate the effect of working surface roughness on electrostatic charge generation. This work aims to investigate the working mechanism of surface roughness effect on electrostatic charge generation. Two kinds of granule materials, PVC and PP, with original shapes of cylinder or semi-cylinder, and the bottom diameter of 4 mm and height of 2 mm were used. Granular surface roughness was measured using Laser Scanning Microscope (LSM) to an accuracy of 0.5 nm. The roughness of granules ranged from 0.140 to 8.600 μm and its effects on electrostatic charge generation in combination with elements such as humidity, granule material, granule height, contact area and others were analyzed.

2. Experimental method

2.1. Granule surface treatment and measurement

In this work, two kinds of granules made of PVC or PP were used. Fresh particles were used in pneumatic conveying system and most of them were broken into smaller granules [20]. In order to estimate the electrostatics generation in a pneumatic conveying system by characterizing a single granule [10]. In this work, three granule bottom-shapes were chosen as the working surface, namely, circular, rectangular and semi-circular shape (shown in Fig. 1). Granular shapes were kept constant during the experiments because as the granules slide down into the Faraday cage, the particle-wall impact has little effect on their bodies. Unless otherwise stated, measurements (surface roughness, electrostatic charge generation and so on) involving granule surface are all based on the bottom face. To obtain various extents of surface roughness, granules were ground using 180-mesh, 400-mesh, 800-mesh, 1200-mesh, and 2000-mesh sand paper separately, and the smallest one was polished. The corresponding sandpaper mesh and surface roughness are shown in Table 1. Two grinding pastes were selected as 0.5 μm and 5 μm, respectively. It is noted that after grinding, each granule was cleaned with compressed air and no contamination particles were detected using Laser Scanning Microscope (LSM). The mass of a granule was measured using an electronic balance to an accuracy of 10^{-4} g and the charge-to-mass ratio of the granule was then calculated. The length of each side of the sliding face was measured using a micrometer to an accuracy of 10^{-5} m. The radius of granules sampled is 2 mm, the thickness ranges from 1.85 to 2.01 mm and their weight ranges from 34.0 to 38.9 mg (shown in Table 2). In addition, surface roughness and protruded area of contact particle surface were measured using Laser Scanning Microscope (LSM: VK-X200K, made by Keyence Corporation). Its measurement resolution at the Z-axis is 0.5 nm with repeated accuracy (δ): 0.012 μm and the resolution at X-axis is 1 nm with repeated accuracy (3δ): 0.02 μm. In this work, the roughness Ra of the inclined metal plate is far less than 1 μm so it is believed that as a granule slides along the plate, its surface roughness remains constant and is not affected by the plate.

Granule surface roughness Ra was measured as follows. Firstly, the tilting orientation of the plane used for measuring granule Ra was corrected. Secondly, the tilting orientation was evaluated by an equation in terms of "z = ax + by + c", where the parameters a, b, c were obtained using the least square method either in the