Electrostatic charging of single granules by repeated sliding along inclined metal plates

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ABSTRACT

In this work, repeated sliding tests for single granules were investigated for their electrostatics generation. Several factors were considered including granule length-ratio, sliding face shape, sliding times, sliding area, sliding velocity, front-facing edge, plate inclined angle and humidity. Generally, it is found that electrostatics increases with granule length-ratio. Two kinds of granular sliding face shapes were used in this work, half circle and rectangle. Under the same working conditions, a granule with the sliding face shape of half-circle tends to produce more electrostatics than that of rectangle. In addition, the efficiency of granule charge generation increases with sliding times although the amount of impact charge is decreased by the initial charge. Electrostatics increases with sliding area, which is independent of granule sliding-face shape and sliding times. Electrostatics also increases with granule sliding velocity. Front-facing sliding with a short edge tends to generate more electrostatics than that with a long edge. In this work, three sliding-plate angles were chosen as 30° , 54° , 70° , where granules sliding along the inclined plate at 54° acquired the highest electrostatics in comparison with other two angles. Humidity has significant effect on electrostatics as that electrostatics decreases with humidity. At lower relative humidity, the granule length-ratio is found to have more effect on electrostatics.

Keywords: Electrostatics; Sliding; Single granule; Granule shape.

1. Introduction

Contact or friction charge (triboelectrification) is induced by sudden contact and separation of two materials. The magnitude and the sign of the charge depend on the difference between the work functions or Fermi energy levels of both materials. Triboelectrification has been studied and commercially used for coal cleaning due to its effectiveness and simplicity [1-3] as well as applied for purifying a variety of materials including minerals, PVC and fly ash [4-6] (separating unburned carbon from coal combustion fly ash [4]). Triboelectrostatic separation of fly ash is usually accomplished by triboelectrification of the fly ash passing through two oppositely charged electrodes. Generally, charge generation depends not only on relative conductivities of the materials in contact, but also on the surface situation, such as particle size, shape, the presence of sharp edges, surface roughness, lattice defects, contamination, temperature, humidity [5-7] and so on. In 1969, Cole et al. [8] found that the charge transfer followed a decelerating exponential function with the number of granule-wall collisions and then established one of the earliest theories. Guardiola et al. [9] and Saleh et al. [10] argued that electrostatics increases with granule size as well as the flow velocity of the pneumatic conveying system. In addition, they found that the relative humidity is another significant factor effect on the electrostatics. Ban et al.[11] investigated the characteristics of particle charging and the effects of charging velocity by utilizing a non-intrusive, laser based, phase Doppler velocimeter system, where they gained the charge distribution and the effect of charging velocity on spherical silica particles and some initial separation data for coal and carbon /silica model mixtures. Nomura et al.[12] reported that the absolute value of the saturated specific tribocharging of the powder decreases with increasing humidity. Matsusaka and Masuda [13] developed a novel design on granule charging by repeated impacts on a wall and employed this formulation to investigate a particulate flow system with

adjustable amounts of charge, and concurrently they developed a theoretical study to examine the granule charge distribution. Recently, Saleh et al. [10] investigated the effects of granule size, solid flow rate, and air velocity on tribocharging. Yao et al. [14] integrated electrometer, electrical capacitance tomography (ECT), high-speed camera and particle image velocimetry (PIV) to investigate the electrostatics of granules in pneumatic conveying systems and confirm an “equilibrium state” for electrostatics generation, which is independent of pneumatic conveying flow rates. When a single granule underwent repeated sliding along the plate, electrostatic charge generated increased with sliding times until reached “equilibrium state” with the equilibrium charge. It is found (Yao et al. [15]) that the equilibrium charge is dominated by several factors, such as sliding area, granule length-ratio, sliding face shape, sliding times, sliding velocity, front-facing edge, and so on.

With more renewable energy generated, power plants across the world have been converted to co-firing with a mixture of coal and biomass as well as solely biomass fuelling. Compared to coal, the shape of biomass particles is complex (enlongated due to their fibrous structure) and the size distribution is over a much wider range. For example, in the work carried by Coombes and Yan [16], the size of willow particle distributes from 180-5600 μm . In addition, Guo et al. [17] proposed an integrated model to describe the quantitative relationship between angle of internal friction and granular shape factors, which agreed well with the experimental data. Yao and Wang [18] carried out a comprehensive study of the effects of granular size and shape on electrostatics in recycled pneumatic conveying systems. It is found that granule size and shape causes significant effect on electrostatics generation. On the other hand, electrostatics of granular flow is very complex due to a lot of granules involved in the charging or discharging progress. Investigation of single granules for the impact, contact and behavior may be helpful to fully understand the elementary process of

electrostatics generation. “Impact charging experiments” [19-22] for single polymer granules (3mm) were carried out to study the electrostatic charge generation by impact on a metal plate. Single granule with diameter as 30 mm was tested for its electrostatics generation by Matsusaka et al. [13] as well as 100 μm granules by Matsuyama et al. [23].

Yao et al. [14,24] and Yao and Wang [18] have done series work involving granular electrostatics in pneumatic conveying systems, where the electrostatics working is very complex i.e. unstable flows, easy-broken pipeline, noises, granule erosion, and granule attrition and so on. As such, a miniature and controllable system was designed in this work, which is able to handle single granule electrostatics generation. So far, there is little publication to make clarification on this point. In this work, more than thousands of granules were processed and the results obtained could meet well with model equations. The equations acquired from the experimental measurement can be used to compare the capability of charge generation via sliding times.

This paper is organized as following. Introduction is listed in the first section. Experimental design is introduced in the second section including experiment apparatus, granule properties and specific experimental design. Some basic variables are defined in this section, including granule, length-ratio, and charge. In the third section, the effects of length-ratio, sliding area, sliding velocity, front-facing edge, plate inclined angle, initial charge and relative humidity on charge generation are analyzed. In the last section, conclusions are summarized.

2 Experiment design

2.1. Experiment apparatus

The experiment apparatus used in the present study is shown in Fig. 1. A stainless

steel plate (labeled as 2, thickness 2mm, length 188mm) was placed at an inclined position from a stand to allow the sample granule to slide smoothly under the gravity effect. A single granule was put at the top of the pipe and allowed to slide down along the pipe wall and fall into the Faraday cage (3, TR8031, Advantest Corporation, Japan). A high-speed camera (7, OLYMPUS, i-speed LT) recorded the whole sliding process for determination of the sliding time for the respective sliding velocity. The Faraday cage was connected to an electrometer (5, Advantest R8252 Digital Electrometer, Advantest Corporation, Japan) with a cable linked to a computer (6). At each test, electrostatic charges were generated on the granule and the pipe wall with opposite polarity via triboelectrification, which could be detected by the electrometer (5) as the granule fell into the Faraday cage (3). The data were automatically stored in the computer (6) at intervals of 0.1 s. The mass of single granule was measured using an electronic balance to an accuracy of 10^{-4} g and the mass-to-charge variation of the granule was then calculated. For all test, the metal plate (2), Faraday cage (3) and electrometer (5) were all grounded. A metal plate (8) was used for particles to discharge any residual charges. To achieve a stable (non-rolling) model of sliding, the largest face (shadowed in Fig.2 (b)) was chosen as the sliding face. In addition, from the movie taken by the high-speed camera (7), the cases of granule sliding were chosen by straight sliding along the metal rather than curve sliding. In this work, 50 half-circle particles and 80 rectangular particles were tested in thousands times.

2.2. Granule properties

Polyvinyl chloride (PVC) granules used in this study have two basic granule shapes: half-circle and rectangular, as shown in Fig.2 (a) (b). Compositional faces of each basic column are shown in Fig.2 (b). For rectangular granule (shown in Fig. 2(b)-1), the sliding (shadow) face was in the shape of a rectangle and for the half-circle

granule (shown in Fig. 2(b)-2), the sliding (shadow) face was in the shape of a half-circle. Four types of sliding are defined for all granules in Fig. 2(c).

In this work, all tests were carried out with the largest granule face in order to avoid granule rolling or rotating during its sliding on the metal plate, for example, the shape of half-circle was chosen as the sliding surface for a half-cylinder granule and the largest rectangular face was chosen as the sliding surface for a rectangular granule. Single granule size was generally characterized by length (L) and width (W) (shown in Fig.2 (b)), which was measured by a micrometer to an accuracy of 10^{-4} m. Based on the length and width, the sliding area could be calculated. For all granules tested in this work, the length of the rectangular granules ranges from 2 to 6mm and corresponding area from 4 to 16mm², the length of half-cylinder granules ranges from 3 to 5 mm with the similar area as rectangular granules.

2.3. Single granule repeated slidings

One sample granule was placed at the top of the inclined plate and then allowed to slide along the plate and fall into the Faraday cage. After the test data were recorded, the granule was taken out of the Faraday cage and repeated sliding along the metal plate. An anti-electrostatics forceps was used to hold the granule, take it out of the cage, and put it back to the top of the plate to start another sliding. It should be noted that the forceps were used to hold the side-faces of the granule without touching the sliding face. There might be a small amount of charge transfer during the relocation of the tested granule, which was ignored in this work. The sliding repeated in several times until granules electrostatics reached the “saturated” stage, where the amount of charge on the granules remained constant. Such constant charge is known as ‘equilibrium charge’. It is assumed that the interval between each slide is constant so that the charge relaxation based on the elapsed time is constant. All sampled

granules sliding with different front-facing edges are shown in Fig.2 (c). Fig.2 (c)(1)(3) show the orientation during sliding on the long edge for a rectangular granule and half-cylinder granule respectively, and (2)(4) show that on the short edge for these two types of granules, respectively. The inclined plate was set at 30°, 54° and 70°. All experiments were carried out in triplicate under the same conditions and the presented results were the averaged values. The humidity of the environment was set at 50% and the temperature at 20°C for general test. In addition, several humidity levels from 30% to 85% were tested for its effect on electrostatics generation. As noted above, each test used the most stable face of a granule as the sliding face to avoid granule rolling (Yao and Wang) [18] and rotating. After each test, single granules were discharged separately for more than 24 hours. This choice of relaxation time scale is based on our previous studies [18, 24], where most charges can be dissipated after 24-hour discharging. A little amount of charge may be generated as the granule picked up from the metal, which can be ignored because it is fairly low in comparison with the charges generated as sliding along the metal plate. For all granules tested, the sliding surface has similar roughness and flatness. The metal plate surface is so smooth that will not modify granule sliding surface roughness. As such the effect of granular surface roughness on charge generation can be ignored in this work.

2.4. Definitions

Length-ratio. The schematics of the sliding faces for both types of granules are shown in Fig. 2(b). The length-ratio is defined as: Length-ratio = length (L)/width (W), $L > W$. The sliding face of rectangle granules is shown in Fig. 2(b)-1, where L is the length of the rectangle granule, and W is the width. Similarly, for the half-circle granules (Fig. 2(b)-2), length-ratio is defined as: Length-ratio = length (L)/width (W),

$L > W$, L is the length of the half-circle granule and W is the width.

Yao and Wang [18] and Yao et al. [24] found that longilineal and thin granules tend to have more charge generation in comparison with other granules. It is suggested that electrostatics charge tends to generate more along the longer edge of granules. As such, “length-ratio” is defined as the ratio of length to width of a particular granule to evaluate granular shape effect on electrostatics generation.

$$\text{Length-ratio}(Lr) = \frac{\text{Length}(L)}{\text{Width}(W)} \quad L > W \quad (1)$$

Charge density

$$\text{Charge} \cdot \text{to} \cdot \text{length-ratio}(q_l) = \frac{\text{Charge}}{\text{Length-ratio}} (C) \quad (2)$$

$$\text{Charge} \cdot \text{density}(q_d) = \frac{\text{Charge}}{\text{Area}} (C / \text{mm}^2) \quad (3)$$

$$\text{Charge} \cdot \text{density} \cdot \text{to} \cdot \text{length-ratio}(q_r) = \frac{\text{Charge} \cdot \text{density}}{\text{Length-ratio}} (C / \text{mm}^2) \quad (4)$$

In this work, several factors involving electrostatics generation were considered, i.e. front-facing edge, length-ratio, sliding area, relative humidity, and plate inclined-angle. To illustrate the individual contribution of these factors on electrostatics, several electrostatic functions are defined as shown in Eqs.(1)-(4). Particularly, under consideration the effect of granular contacting-surface area, the terms of charge density and charge density to length-ratio are used to assess the capability of granule charge-generation. The charge density to length ratio is defined to include area (mm^2) with the objective to normalize the contributions from it. For example, to examine the front-facing edge effect on granular electrostatics, the term charge density to length-ratio is used to assess the capability of granule charge-generation because the effects from area and length-ratio are considered.

3 Results and discussion

3.1. Length-ratio effect

Yao and Wang [18] found that granular size and shape do have significant effect on granule electrostatics generation for case studies of both bulk granules in a pneumatic conveying system and single granule sliding along a metal plate. In this work, a single granule with a specific shape was investigated for electrostatics generation. The length-ratio is defined in Eq.(1) and its effect on granule electrostatics was investigated as shown in Fig. 3. The experiments used PVC granules with two kinds of face-shape, half-circular and rectangular. Each granule slid six times along the inclined steel plate at 54°. All tests had short edge as the front-facing edge (as shown in Fig. 2 (c) (2) (4)) and the humidity was at 50% (RH=50%). For all tests shown in Fig. 3, the **charge density** follows a linear relationship with length-ratio, which indicates that electrostatics increases proportionally to granule length-ratio. Such finding is independent of granular face shape and agrees well with previous studies [18]. The least-square fitting for the linear function of **charge density** to length-ratio relationship can be given by,

$$q_d = AL_r + B \quad (5)$$

The A or B values for each test are listed in Table 1. For all tests, the value A increases with the sliding time, which indicates that the efficiency of granule charge generation increases with the sliding time. With more sliding, granule tends to acquire more charges afterwards, which is independent of how many experimental measurement data collected. On the other hand, based on granule shape effect considered, a granule with half-circle shape does produce more electrostatics than that with a rectangular shape does. This may be due to the fact that the “half-circle” shape tends to be narrower with sharp angle in comparison with the ‘rectangular’ shape. From Fig.3, the B in the **Eq.(5)** is equal to the interceptive value of **charge**

density where the length–ratio is equal to 1.0. From Fig. 3 and Table 1, it is seen that B (absolute) value almost increase with sliding times, which indicates that the electrostatics increases with sliding times. It is reasonable because the electrostatics charge is able to accumulate with sliding times. In addition, B value for the granule with “half-circle” sliding face tends to be higher than that with “rectangle”.

As mentioned above, it may be explained by the fact that the “half-circle” shape is narrower with sharp angle than the ‘rectangular’ shape. Such result agrees well with previous works [10, 18]. Yao and Wang [18] carried out triboelectric tests based on pneumatic transport of PVC granules and argued that the angular granules allow a stronger charge transfer. Saleh et al. [10] performed experimental work on horizontal pneumatic flow and found that granules with irregular shapes tend to have better quality of charge generation.

Fig. 4 presents the relationship between charge density, length-ratio and number of sliding times. It is found that for either half-circle granule or rectangular granule, charge density increases with length ratio, which is independent of the sliding times. In addition, charge density increases with sliding times. It is seen that after several times (eighth time), sliding charge density reaches the saturated stage, which is independent of length-ratio. It is suggested that electrostatic charges on the granular body increases with sliding times due to limit in the charging capacity. Once it reaches the fully charged level (termed as the “saturated” stage), the charge density remains at constant level. It is found that all granules tested reach the “saturated state” after eight times. It is known that granule-wall contact can cause electrostatic charge generation on granule surface and wall, which gives rise to charging effect on granules. In the work system, due to the metal plate being grounded, charges generated at the pipe wall would quickly disappear. On the other hand, if a granule was originally charged, electrostatics charges on the granule surface would

accumulate. After sliding in several times, electrostatics charge accumulated at the granule reached a full level, as noted above as “saturated” stage. In this work, several factors were found to affect the electrostatics saturated stage, such as sliding area, sliding velocity, front-facing edge, plate inclined angle, initial charge and relative humidity. They are analyzed in the following sections one by one.

3.2 Sliding area effect

Fig.5 shows the relationship between electrostatics (in terms of **charge to length-ratio**) and the sliding area within the duration of 1st and 2nd sliding. The granules slid on the face with the shape of “half-circle” and “rectangle”, respectively. For both cases (Fig.5(a),(b)), it is seen that the electrostatics (**charge to length-ratio**) increases with sliding area, which is independent of granule sliding-face shape. This result agrees well with the experimental findings by Cheng et al.[25], who investigated electrostatics generation in a downer reactor and observed that the averaged induced currents increase with granule diameter. In addition, this conclusion also agrees well with the experiment work done by Marra et al.[26], where they studied tribocharging of aerosols of fine phosphate rock concentrations and concluded that electrostatics charge generated increases with granule size. In 1976, Masuda et al. [27] found that during granule-wall elastic collisions the contact area was different with granule size. As such, all above findings suggested that electrostatics generation increases with contact area. In addition, Fig. 5 shows that with the same area, half-circle granules tend to acquire more electrostatics charge than rectangle granules, which agrees with the conclusion obtained by granule length-ratio in section 3.1.

Fig. 6(a) presents the relationship between electrostatics in terms of **charge density to length ratio** with sliding-face area and length-ratio. Again, it is seen that electrostatics increases with sliding-face area, which is independent of length-ratio. In

addition, electrostatics increases with length-ratio, which is also independent of sliding-face area. As for considering both factors, it is seen that the capability of granular charge generation increases with either granular sliding-face area or length-ratio. Furthermore, it should be noted that in Fig.6 (a), the increase due to granular length ratio is much higher than that due to granular area. As such, it is suggested that granular length-ratio plays a more significant role in electrostatics generation in comparison with sliding-face area.

3.3. *Sliding velocity effect*

Fig. 6(b)-(c) shows the sliding velocity effect on electrostatic charge generation. Fig. 6(b) demonstrates that for both granular sliding-face shapes (either half-circle or rectangle), the electrostatics (charge density to length-ratio) increases with sliding velocity. It suggests that the generation of electrostatic charge increases with granule sliding velocity. In addition, it is seen that at the same sliding velocity, sliding on a half-circle face causes more electrostatics generation than that on a rectangular face, which is consistent with the result stated in the sections 3.1, 3.2. This may be due to the fact that the shape of “half-circle” tends to be narrower with sharp angle in comparison with that of “rectangle”. Fig. 6 (c) shows the relationship between granule sliding velocity and granule length-ratio. It is seen that the granular sliding velocity increases with granular length-ratio. Such statement is consistent with the argument that electrostatics generation increases with either granule length-ratio or granules sharper angle because both factor give rise to higher sliding velocity and eventually leads to higher electrostatics charge generation. Fig. 2(a) presents the granule sliding along the inclined plate, which was recorded by a high-speed camera with time interval 0.02s for 0.2s. As the granule slid along the inclined plate, the whole sliding procedure was recorded by the high-speed camera. The granule sliding velocity can

be calculated through dividing the sliding distance by the time duration recorded. In this work, the granule sliding velocity is 0.6-0.7m/s. The effects of granule velocity on charge generation were investigated by other experimental studies [10, 25, 27] in terms of “granule-wall impact”. They all concluded that the granule-wall collision force increases with granule impact velocity due to increasing particle momentum, which excites more electrons to be released from the collision. It seems reasonable because a granule with higher sliding velocity generates more electrostatics charge due to higher particle momentum to excite more electrons released from the sliding.

3.4 Front-facing edge effect

Fig.7 (a)-(b) show the front-facing edge effect on granular electrostatics generation (in terms of charge density) for half-circle granule and rectangular granule, respectively. For both cases, granules sliding along the plate with the short edge (Fig. 2(c)-2 and 4) as the front-facing edge were able to generate more electrostatics than that with long edge (Fig. 2(c)-1 and 3) as the front-facing edge. As such, it is concluded that granule sliding direction does have significant effect on electrostatics generation. The working mechanism might be due to the sliding velocity. Fig. 7 (c)-(d) show the relationship between sliding direction and sliding velocity for half-circle granule and rectangular granule, respectively. For both cases, granules slide faster by using the short edge as the front-facing edge than that by using the long edge as the front-facing edge. It may be due to the fact that the resistance on granules sliding in the direction of the short edge is smaller than that of granules sliding in the direction of long edge. As a result, granules gain high velocity and more momentum and excite more electrons for release from the sliding, which can be further explained by sliding velocity working mechanism shown in section 3.3.

3.5. Plate inclined angle effect

Fig. 7(e) presents the electrostatics charge generated for rectangular-shape granules at three plate inclined angles (30° , 54° , 70°). It shows that granules sliding along the inclined angle at 54° plate acquire the highest electrostatics charge (presented by charge density) in comparison with other two cases (30° , 70°). The amounts of electrostatics charge generated at 30° inclined plate and 70° inclined plate have no significant difference but both are obviously lower than that of 54° inclined plate. The results are in good agreement with the work by Ema etc.[28], who investigated the effect of impact angle on the triboelectric charging. The author used an inclined target and observed that the electrostatics charge increased with the impact angle up to 60° and then decreased. The working mechanism might depend on the balance of two factors, namely, friction force effect on granule and the granule sliding velocity. The friction force decreases with the inclined angle but the sliding velocity increases with it. Both factors work against each other and the final result depends on the stronger side. For example, at 30° , the friction force tends to have more effect on electrostatics generation but the granule sliding velocity is fairly low at such low inclined angle. In contrast, at 70° , the granule sliding velocity is obviously higher than that at 30° so has more effect on electrostatics generation but the friction is fairly low due to the large inclined angle. At 54° , compared to other two cases (30° or 70°), both friction and granule sliding velocity are increased so that they lead to more electrostatics generation.

3.6. Dependence of contact charge on the initial charge

In the repeated sliding experiments, the charge carried by granules before sliding is called “initial charge” and the charge obtained after sliding is called “impact charge”. Fig.8 (a) (b) presents the granule length-ratio effect on electrostatics for the first and

second sliding for half-circle granule and rectangular granule, respectively. It is found that, for both cases, the impact charge acquired after the second sliding is much higher than that after the first sliding. The value of the second impact charge is about two-three times higher than the first impact charge. It is suggested that conduction is a significant factor affecting the repeated-sliding charging. Nominal insulators may not be nonconductive because a large amount of charges was found to be transferred from the immediate sliding area as granules slid [29]. After the first sliding, little amount of charge generated stayed on the sliding surface. It increased the expected effect of conduction and therefore increased the incremental charge transfer during the second sliding.

Fig.8 (c) presents the charging status for the four typical granules with various length ratios. It is found that the granules basically receive negative charges by sliding along the stainless steel plate, and the amount of impact charge decreases as the initial charge approaches a certain limiting value, for example, in Figure 8(c), as the initial charge is lower than $-7 \text{ nC/g}\cdot\text{mm}^2$, the impact charge decreases with the initial charge linearly. It is due to the fact that each granule has a certain charging capability. As a granule acquires a large amount of initial charge, it tends to acquire less amount of impact charge after the initial sliding. The limiting value is an **equilibrium** value. This indicates that initial charge has an effect on electrostatics generation. In addition, from Fig.8 (c), it can be seen that the amount of impact charge (absolute value) increases with granule length-ratio. The granule with higher length ratio generates more impact charge, which agrees well with the conclusion obtained from Fig.3 saying that electrostatics generated increases linearly with granular length-ratio. As such, it can be concluded that either after the initial sliding or repeated sliding, granules with larger length-ratio tend to generate more electrostatics charge.

3.7. Relative humidity effect

The sampled particles were placed in environments with specified relative humidity for 24 hours. The point chart of the average charge versus relative humidity is shown in Fig.9. Each point represents the overall average charge of granules for a range of length-ratios at a fixed temperature and specified relative humidity. In Fig.9(b), it is seen that as humidity RH=30%, the electrostatics (charge density) is found in the range $1.6\sim22.4\times10^{-9}\text{ C/mm}^2$. In contrast, as RH=85%, the corresponding electrostatics is found in the range $5\sim17\times10^{-8}\text{ C/g}\cdot\text{mm}^2$. It is clear that the electrostatics at RH=85% is fairly lower than that at RH=30% around two orders of magnitude. The analysis could yield three observations. First, there is a general decrease in the amount of charge density (net charge transferred) as relative humidity increases. Second, In this work, as the air moisture content exceeded the cutoff relative humidity 85%, the transferred charge could not be measured. It can be explained by the fact that there are sufficient amount of water molecules attaching on the surface of a granule at RH=85%. Henceforth, RH=85% can be taken as the critical relative humidity in this study that is quite close to the measurement by Ireland [29] at RH=80%. As a good conductor, water will promote electrostatics charge to transfer from high potential to low potential and cause discharging. Third, at lower relative humidity, granule length-ratio does have more significant effect on charge generation. It can be further supported by Yao et al. [14], who studied electrostatics of granular flow in a pneumatic conveying system and found that granule charge densities were lower at high humidity levels and vice versa. Several mechanisms could be used to explain the influence of humidity on electrostatics charge generation of granules. Saleh et al. [10] favored the explanation that adsorbed moisture on the surface of granules increases the conductivity of surfaces in contact and intensifies the charge relaxation phenomenon. Greason [30] gave an interpretation as due to increased leakage

caused by a decrease in the effective resistance to ground.

4 Conclusions

In this work, repeated sliding tests with single granules were investigated for their electrostatics generation. Several significant factors were considered for their effects on electrostatics generation, such as granule length-ratio, sliding face shape, sliding times, sliding area, sliding velocity, front-facing edge, sliding-plate inclined-angle and humidity. Conclusions can be derived as followings.

First, electrostatics increases with granule length-ratio. This may be due to the fact that electrostatics increases with granule sliding velocity and the sliding velocity increases with granule length-ratio.

Second, two kinds of granule sliding face shapes (half circle and rectangle) were used in this work. Under the same working conditions, a granule with the shape of half-circle does produce more electrostatics charge than that with the shape of rectangle.

Third, the efficiency of electrostatics charge generation increases with sliding times. For example, the impact charge acquired from the second sliding is much higher than that from the first sliding. The electrostatics increases with sliding times until reach the “saturated state”

Fourth, the amount of impact charge decreases with the initial charge. Electrostatics increases with sliding area, which is independent of granule sliding-face shape and sliding times. Front-facing sliding with a short edge tends to generate more electrostatics than that with a long edge.

Fifth, in this work, three sliding-plate angles were chosen. Granules sliding along the inclined plate with an angle of inclination of 54° acquired the highest electrostatics in comparison with the other two cases ($30^\circ, 70^\circ$). This was due to the effect of friction

between granule and plate wall and granule sliding velocity.

Last, humidity does affect electrostatics generation. There is a general decrease in the amount of **charge density** as relative humidity increases. The critical relative humidity of PVC granules is found to be at 85%. At lower relative humidity, the granule length-ratio does have more effect on the charge generation.

Nomenclature

L_r	granular length ratio, dimensionless
L	granule length, mm
q_d	charge density, C/mm²
q_l	charge to length-ratio, C
q_r	charge density to length-ratio, C/mm²
W	granule width, mm

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References

- [1] Y. T. Shih, D. Gidaspow, D. Wasan, Hydrodynamics of electrofluidization – separation of pyrites from coal, AIChE J. 33 (1987) 1322-1333.
- [2] J. P. Baltrus, J. R. Diehl, Y. Soong, W. Sands, Triboelectrostatic separation of fly ash and charge reversal, Fuel 81(2002) 757-762.
- [3] R. S. Blissett, N. A. Rowson, A review of the multi-component utilisation of coal fly

ash, Fuel 97(2012) 1-23.

[4] H. Ban, T. X. Li, J. C. Hower, J. L. Schaefer, J. M. Stencel, Dry triboelectrostatic beneficiation of fly ash, Fuel 76 (1997) 801-805.

[5] H.R. Manouchehri, K.H. Rao, K.S.E. Forssberg, Review of electrical separation methods Part 1: Fundamental aspects, Miner Metall Proc 17(2000) 23-36.

[6] H.R. Manouchehri, K.H.Rao, K.S.E.Forssberg, Review of electrical separation methods Part 2: Practical considerations, Miner Metall Proc 17(2000) 139-166.

[7] M. M. Maroto-Valer, D. N. Taulbee, J. C. Hower, Novel separation of the differing forms of unburned carbon present in fly ash using density gradient centrifugation, Energ Fuel 13 (1999) 947-953.

[8] B. N. Cole, M. R. Baum, F. R. Mobbs, An investigation of electrostatic charging effects in high-speed gas solids pipe flows, P I Mech Eng 184(1969-1970), 77-83.

[9] J. Guardiola, V. Rojo, G. Ramos, Influence of granule size, fluidization velocity and relative humidity on fluidized bed electrostatics, J Electrostat 37(1996) 1-20.

[10] K. Saleh, A.T. Ndama, P. Guigon, Relevant parameters involved in tribocharging of powders during dilute phase pneumatic transport, Chem Eng Res Des 89(2011) 2582-2597.

[11] H. Ban, L. John, K.S. Schaefer, M.S. John, Particle tribocharging characteristics relating to electrostatic dry coal cleaning, Fuel 73 (1994) 1108-1113.

[12] T. Nomura, T. Satoh, H. Masuda, The environment humidity effect on the tribo-charge of powder, Powder Technol. 135/136 (2003) 43-49.

[13] S. Matsusaka, H. Masuda, Electrostatics of granules, Adv. Powder Technol 14 (2003) 143-166.

[14] J. Yao, Y. Zhang, C. H. Wang, Y. C. Liang, On the electrostatic equilibrium of granular flow in pneumatic conveying systems, AIChE J 52(2006) 3775-3793.

[15] J.Yao, F.Zhou, Y.L.Zhao, On the charge generation and electrostatic equilibrium

for single granules, *Particuology* 29(2016),126-134

[16] J.R. Coombes, Y. Yan, Experimental investigations into the flow characteristics of pneumatically conveyed biomass particles using an electrostatic sensor array, *Fuel* 151 (2015) 11-20.

[17] Z.G. Guo, X.L. Chen, Y. Xu, H.F. Liu, Effect of granular shape on angle of internal friction of binary granular system, *Fuel* 150 (2015) 298-304.

[18] J. Yao, C.H. Wang, Granular size and shape effect on electrostatics in pneumatic conveying systems, *Chem Eng Sci.* 61(2006) 3858–3874.

[19] N. Masui, Y. Murata, Electrification of polymer granules by impact on a metal plate, *Jpn J Appl Phys* 22 (1983) 1057–1062.

[20] N. Masui, Y. Murata, Mechanisms of charge build-up on a polymer granule by repeated impact, *Jpn J Appl Phys* 23 (1984) 550–555.

[21] H. Yamamoto, B. Scarlett, Triboelectric charging of polymer granules by impact, *Granule Characterization* 3(1986) 117–121.

[22] T. Matsuyama, H. Yamamoto, Charge relaxation process dominates contact charging of a granule in atmospheric conditions II. General model, *J Phys D Appl Phys* 30 (1996) 2170–2175.

[23] T. Matsuyama, M. Ogu, H. Yamamoto, J. C. M. Marijnissen, B. Scarlett, Impact charging experiments with single granules of hundred micrometre size, *Powder Technol* 135/136 (2003) 14–22.

[24] J. Yao, Y. Zhang, C.H. Wang, S. Matsusaka, H. Masuda, Electrostatics of the granular flow in a pneumatic conveying system, *Ind Eng Chem Res* 43 (2004)7181-7199.

[25] Y.P. Cheng, D.Y.J Lau, G. Q. Guan, C. Fushimi, A. Tsutsumi, C. H. Wang, Experimental and numerical investigations on the electrostatics generation and transport in the downer reactor of a triple-bed combined circulating fluidized bed, *Ind*

Eng Chem Res 51 (2012) 14258–14267.

[26] W. D. Marra, M. V. Rodrigues, R. G. A. Miranda, M. A. S. Barrozo, J. R. Coury, The effect of the generation and handling in the acquired electrostatic charge in airborne granules, Powder Technol. 191(2009) 299-308.

[27] H. Masuda, T. Komatsu, K. Linoya, The static electrification of granules in gas–solids pipe flow, AIChE J. 3 (1976) 558–564.

[28] A. Ema, D. Yasuda, K. Tanoue, H. Masuda, Tribo-charge and rebound characteristics of particles impact on inclined or rotating metal target, Powder Technol. 135-136(2003) 2-13.

[29] P. M. Ireland, Contact charge accumulation and separation discharge, J. Electrostat. 67(2009) 462-467.

[30] W. D. Greason, Investigation of a test methodology for triboelectrification, J. Electrostat. 49 (2000) 245-256.

Table 1

A and B values Eq.(5) for half-circle/rectangle granules

Sliding times	Half-circle granules		Rectangle granules	
	A	B	A	B
1 st	1.66	-0.20	0.92	-0.15
2 nd	2.50	-1.13	2.05	-0.38
3 rd	3.07	-1.50	2.35	-1.0
4 th	3.70	-2.63	2.94	-1.80
5 th	2.32	-3.50	1.88	-3.00
6 th	5.00	-4.38	3.12	-4.06

Figure 1

Fig. 1. Particle charging setup: 1. stand; 2. metal plate; 3. Faraday cage; 4. single particle; 5. Electrometer; 6. PC; 7. High-speed camera; 8. metal plate.

Figure 2

Fig. 2 Experimental definitions: (a) images taken by a high-speed camera; (b) sampled granule geometry definition (1) rectangular; (2) semi-cylindrical; (c) front-facing edge, rectangle granule (1) long edge, (2) short edge; half-cylinder granule (3) long edge, (4) short edge.

Figure 3

(a)

(b)

(c)

Figure 3 (continued)

Fig. 3 Charge density as a function of the length-ratio for granules sliding along the metal plate at inclined angle 54° , humidity $\text{RH}=50\%$, short edge as the front-facing edge: (a)-(f): 1st- 6th sliding.

Figure 4

(a)

(b)

Fig. 4. Length-ratio and sliding times effect on electrostatics generation (a) half-circle; (b) rectangle.

Figure 5

Fig. 5. Granule sliding area effect on electrostatics generation: (a) 1st sliding; (b) 2nd sliding.

Figure 6

Fig. 6 (a) Area and length-ratio effect on electrostatics; (b) sliding velocity effect on charge generation, half-circle granule, rectangle granule; (c) sliding velocity vs. granule length-ratio (the granule sliding velocity was calculated by the sliding distance divided by time duration recorded by the high-speed camera).

Figure 7

Figure 7 (continued)

Figure 7 (continued)

Fig. 7. (a)-(b) Front-facing edge effect on charge generation, plate inclined angle= 54° (a) half-circle; (b) rectangle; (c)-(d) front-facing edge effect on sliding velocity, plate inclined angle= 54° (c) half-circle, (d) rectangle; (e) plate inclined angle ($30^\circ, 54^\circ, 70^\circ$) effect on charge generation.

Figure 8

Fig. 8. (a)-(b) Comparison of first impact charge and second impact charge (a) half-circle; (b) rectangle; (c) impact charge obtained by charged granules.

Figure 9

Fig. 9. Relative humidity effect on average charge density (a) half-circle; (b) rectangle.

Graphic Abstract