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Granular Attrition Effect on the Electrostatic Behavior in a Pneumatic Conveying System

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Introduction

Granular material is commonly used in solid-handling or pneumatic conveying systems in the energy, chemical, pharmaceutical, and material processing industries. Various sizes and shapes of particles are commonly observed in these granular systems due to repeated mechanical attrition caused by interactions between granular material with system parts (such as feeder, valves, pipe wall and so on). During the particle attrition processes, solid particles also have a natural tendency to acquire electrostatic charges due to collisions with surfaces of a different material type. Electrostatics and the associated charge generation mechanisms in such system are complex and not fully understood. Here, we provide an analysis of the electrostatics and charge variation taking place in the conveying system by characterising the size and shape of the granular material.

Electrostatic effects and the associated charge generation mechanisms are complex phenomena and often dependent on a variety of factors such as the physical, chemical and electrical characteristics of the material used and ambient conditions. This may give rise to poor reproducibility of experiments where such phenomena are the main focus of investigation. As a result, the number of works reported in the literature which involves measuring or calculating electrical charges on particles in granular flow systems has been limited due to the inherent difficulties in such investigations. Zhang et al.[1] carried out a comprehensive study of the effects of electrostatic forces on cohesive particles. Based on their experimental data on instantaneous velocities of shale particles in a dilute gas/solid system, it was found that the particles oscillate about the mean values in a chaotic manner. The velocity distribution could be approximated by the Maxwellian distribution function and kinetic theory was a very promising approach to describe gas/particle flow systems. Matsusaka and Masuda[2] developed a formulation for the variation of particle charging caused by repeated impacts on a wall and employed the formulation to particle charging in a granular flow where each particle carried a different amount of charge. They then analysed theoretically the particle charge distribution. Nieh et al.[3] considered the effects of various combinations of air humidity, conveying velocities and particle sizes on generation of electrostatic charges and charge distributions in glass beads flowing in a grounded 2-inch copper pipe loop. They demonstrated that air humidity had a significant effect on particle charges. When the system moisture content exceeded a cutoff relative humidity of 76%, the charges on glass beads became effectively neutralized. Kanazawa et al.[4] investigated the charge generation and accumulation on the inner surface of a pipe in a cascade flow system during the transport of powder. It was found that the surface charge density and charge polarity of the pipe wall depended on the successive number of tests and the material of the pipe, respectively. Furthermore, the charging characteristics of the pipe wall during the transport of glass beads and industrial granules were found to depend on the pipe material and transport method.

Granular material behaviour under electrostatic and size effect has attracted some research attention in recent years. As a physical phenomenon to study, many researchers have interests in behaviour of small particles (<<1mm) in a known electric field, where particles used are conductive and the electric field is obtained from a pair of plates with a/d voltage. They found that granular cluster pattern differs with the voltage set (Yeh et al.[5], Sapozhnikov et al.[6], Aranson et al.[7]) and is affected by humidity (Howell et al.[8]). A similar phenomenon was observed (Yao et al.[9]) for larger particles (2.8mm) where three characteristic aggregation patterns (clusters, half-ring and ring) were formed in a vertical pipe due to electrostatic effects in a pneumatic conveying system. Smeltzer et al.[10] performed tests in a pneumatic conveying system using glass beads and found that at constant loadings small particles exhibited greater electrostatic effects over large particles. Gajewski [11] used polystyrene particle in a conveying system and found that higher electrification was achieved in smaller particles. In a different manner, Nieh and Nguyen [3] developed a Faraday probe system for measuring particle charges. With glass beads sized in the range 137-550 *μm*, they established the correlation that large particles carry a large mean charge but a small mean charge-to-mass ratio. However, some contradictory results were obtained by Guardiola et al.[12] who discovered that the level of fluidized bed electrification increases with particle size. For much smaller particles, Brown [13] summarised methods for simultaneous measurement of particle size and charge. In contrast, the effect of particle shape on the electrostatics has never been found in the literature.

Granular attrition due to mechanical effects is a commonly observed phenomenon as reviewed thoroughly by Bemrose and Bridgwater [14]. The rotary valve has been used as a component for studies on pneumatic conveying of granular materials (Rao et al.[15], Zhu et al.[16], Yao et al.[9]). During its operation, especially at a low air flow rate, the rotary valve has been observed to cause significant attrition in the granular material used (Yao et al.[9]).

Experimental design

The experimental setup used is shown in Figure 1. The inner diameter of the pipe was 40 mm and the length of the vertical pipe section between two smooth 90° elbows was 2.97 m, while the horizontal section was 4.12 m in length. The conveying pipe was made of PVC that was transparent, to allow visual observation and had a wall thickness of 5 mm. The entire configuration was held in position using metal castings and supports with various pipe segments jointed by connectors and reinforced by silicone gel. Only PVC (original diameter 3.35-4.1mm, in the shape of cylinders, bulk density 1400 kg/m^3) was used throughout the experiments.

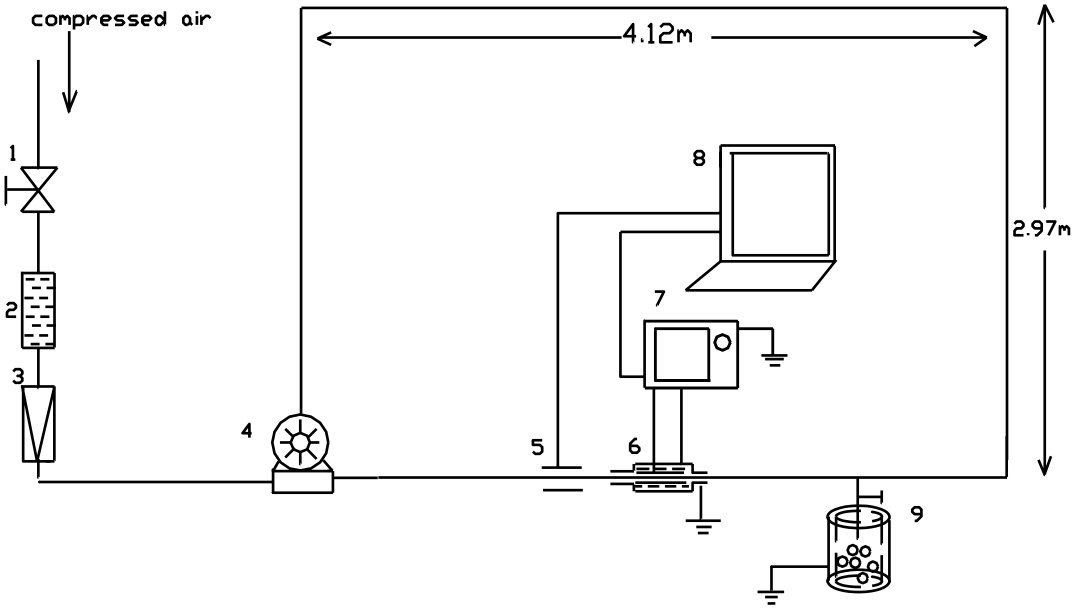


Figure 1 Schematic of the pneumatic conveying facility, 1. air control valve, 2. air dryer (silica gel with indicator-blue), 3. rotameter, 4. rotary valve, 5. modular parametric current transformer (MPCT), 6. induced current measurement, 7. electrometer, 8. computer, 9. Faraday cage.

Air from the compressor mains (air pressure: 75 psi) flowed through the rotary feeder, driving granules fed into the conveying system (Figure 1). A valve (labeled as 1) was used to adjust the air flow rate. The air flow rate was also controlled via a rotameter (labeled as 3) which allowed a maximum flow rate of 2000 L/min. Based on previous work (Yao et al., 2004) three air flow rates were chosen: 1600, 1100 and 950 L/min, and the corresponding air superficial velocity inside the pipe was measured as 21.20, 14.59 and 12.60 m/s. The air humidity was controlled by the dryer at a relative humidity, RH = 5% and this was checked using a high performance digital thermo-hygrometer (RH411, OMEGA Technologics Ltd.) before and after each test. Ambient temperature was controlled at 28 ~ 30 °C. For all cases conducted, the mass of granular material was 1100 g.

During the pneumatic conveying process (Figure 1), collisions between the solid granules and the pipe wall generated electrostatic charges. The current induced along the surface of the pipe wall as a result of these charges was measured as a function of time. This was done by wrapping an aluminum foil sheet tightly over the outer wall of the PVC pipe (labeled as 6). A coaxial line (connected to the high input end of an electrometer (labeled as 7), Advantest R8252 Digital Electrometer, Advantest Corporation, Japan) was connected to the outer surface of the aluminum foil sheet. A polymer film was then wrapped tightly over the aluminum foil sheet to separate this sheet from another aluminum foil sheet whose external surface was connected to the low input end of the coaxial cable. Subsequently, this external layer of aluminum foil sheet was connected to ground and used as an extra electrical shield. The induced current through the pipe wall was measured as a function of time through digital readings from the electrometer (labeled as 7) and stored in a computer (labeled as 8) at intervals of 0.5 s.

Modular Parametric Current Transformer (MPCT: Bergoz Instrumentation, France) allows for current measurement with a resolution of 1 μA using a non-invasive DC beam. The MPCT was installed at the horizontal pipe (labeled as 5). When the granules carrying charge were transported inside the pipe and passed through the instrument, sensitive current readings were generated.

The charge density of the particles was measured by a Faraday cage TR8031 (Advantest Corporation, Japan). The mass of particles collected in the cage was measured using an electronic balance to an accuracy of 10^{-4} g, and the mass-to-charge ratio of the particles was then calculated. Here (Figure 1), the charge of particles was measured online periodically (around 30 minutes between each test). At each test, the air supply was adjusted to let particles enter the Faraday cage (labeled as 9) smoothly and the charge value was automatically recorded by a computer. After each test, particles collected in the Faraday cage were then returned to the conveying system.

During the pneumatic conveying process, charges were produced by the collision or particle-wall impact and the resulting magnitude of the electrostatic generated was around 10^{-9}-10^{-7} A. This is in direct contrast to the case in the absence of granular conveying where the corresponding magnitude was around 10^{-14}-10^{-11} A. Such dramatic changes in induced current has been used as a diagnostic tool for identifying the actual duration of charged solid transport and determination of solid flow rate (Mathur and Klinzing[17]). Such findings also justify the use of induced current for the measurement of solid flow rates at three pre-determined air flow rates in the present study.

The experimental procedures are summarized as follows. Granular material was introduced into the rotary valve and entrained by air flowing from the compressor mains. A specific air flow rate was used to transport a sample of granular material through the pneumatic conveying system for a given time (360 min). At pre-defined time intervals (60 min), air flow and the rotary valve were stopped and the granular material was emptied from the system. A weight-size analysis was carried out by sieving on a representative sample of the material. Then the granular material was discharged for more than 24 hours before the next test. The procedure was repeated for different air flow rates using fresh granular material samples for each separate experiment.

Results and discussion

Here, three typical air flow rates were used and their corresponding flow patterns were observed (Yao et al. [9]) in the horizontal segment of the system. At high air flow rates, particles were seen to be transported as a dilute and homogenous solid phase dispersed in a continuous gas phase. As the flow rates were decreased, particles started to concentrate on the pipe wall from time to time in the form of clusters. These clusters appeared and disappeared intermittently in an unpredictable manner. As the flow rates were reduced further, a fairly stable moving cluster structure was formed which moved along the horizontal pipe at velocities lower than the superficial air velocity.

Granular attrition

The rotary valve was operated as part of a pneumatic conveying system. In this mode of operation, granular attrition was found to occur at three positions, namely the exit, entrance and clearances between the vanes and casing wall of the rotary valve. In particular, the spaces between the vanes and casing wall at the entrance and exit vary in size from a maximum to a minimum and vice versa throughout one rotation cycle of the rotary valve. This phenomenon when coupled with the typically low flowability of granules, especially that of PVC granules, would result in the accumulation and severe attrition of granular material at these spaces. The attrition process is always accompanied with loud noises and violent shaking of the device. As granules moved through the rotary valve, attrition may also occur in the clearance between the vanes and casing wall (Crutchley and Bridgwater[18]). Some attrition may be brought about by direct impacts between the granules and rotary valve vanes or other granules (Konami et al.[19]).

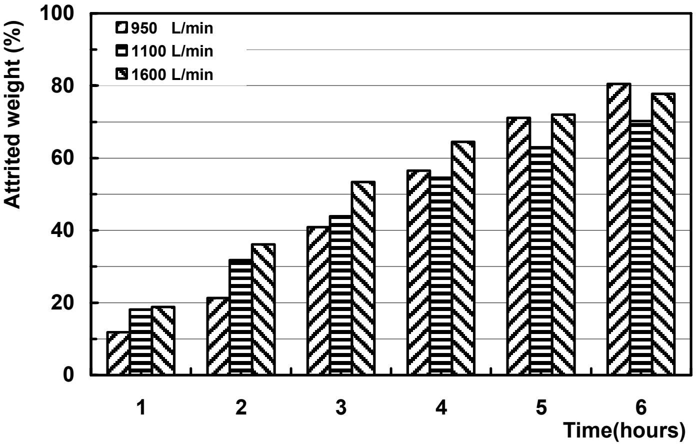


Figure 2. Attrition product weight at three airflow rates in the pneumatic conveying system.

The attrition process within six one-hour tests is presented at three air flow rates (950, 1100, 1600L/min) in Figure 2. It shows that the weight of attrition product increases with time irrespective of air flow rates used in the conveying system. The size of attrition product formed was mainly in the range 2.00-3.35

mm. Sieve cuts were chosen using the golden section principle as 2.00, 2.36, 2.80 and 3.35mm.

Solid flow rate

At three air flow rates, the solid flow rates of original granules and attritited products (undergone 6 hours attrition) were tested and the results for the weight measurements are summarized in Table 1. Our findings show that for all cases, attrition products have a higher solid flow rate in comparison with original granules. Ignoring a small percentage of mass found adhered to the walls of the pipe and the rotary valve, the variation in solid flow rate is caused mostly by granular attrition.

Table 1 Solid flow rates of original/attrited granules in the pneumatic conveying system

	Air flow rate (L/min)					
	950		1100		1600	
Granules	Solid flow rate (g/s)	Weight (g)	Solid flow rate (g/s)	Weight (g)	Solid flow rate (g/s)	Weight (g)
Original	33.63	1100	50.51	1100	63.84	1100
Attrited	37.74	996.70	53.84	992.10	70.11	989.60

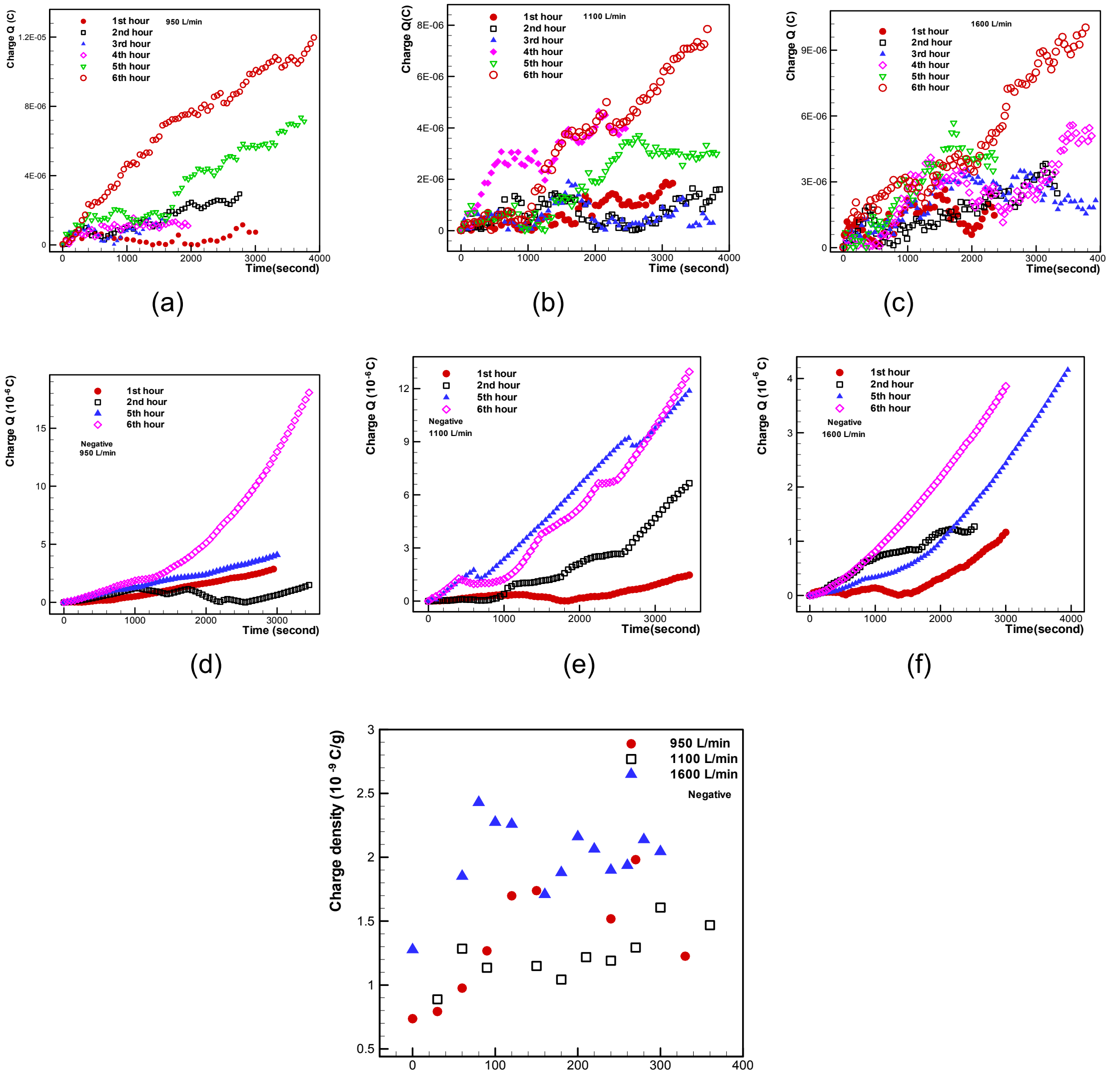
Electrostatics of granular flow

Induced current

Here, attempts are made to analyze the induced current for three flow rates (patterns) described above. As a function of time, induced currents were integrated to obtain the charge Q as shown in Figure 3 (a-c). On the same diagram, each of the six test runs represents the samples collected in one batch experiment conducted. This involved operating the pneumatic conveying system for “n” hours, where n = 1, 2, 3, 4, 5, 6. For instance, the data for the 1st hour refer to a fresh batch experiment conducted at the very beginning of the conveying operation. At the end of the first batch experiment (for a duration of 1 hour), particles are recollected and discharged. Subsequently, these particles are fed back to the conveying loop. After this is done, we start the “2nd” hour experiment and measure the induced current as a function of time (for a duration of 1 hour), counting from the beginning of the second batch experiment. Similar data sets were collected respectively for the 3rd, 4th, 5th, and 6th hour as separate batch experiments. The results show that the charging rate of a later experiment is in general faster than an earlier batch experiment. For instance, the slope of the charge – time curve in the 6th hour (with highest attrition) is much steeper than any of the remaining five batch experiments. As such, electrostatics of granular flow is confirmed to be enhanced with the progress of attrition in the pneumatic conveying system (Figure 2).

MPCT measurement

The equivalent currents for the three flows in the pneumatic conveying system are presented in Figure 3 (d-f), where each data point was obtained by time integration of current readings from the MPCT over around 60 minutes. Charge accumulation rates calculated by the MPCT readings for all cases are seen to increase from the 1st to the 6th hour at growing rates, thus indicating an enhancement of electrostatics of the granular flow in the conveying system. This finding further substantiates the former argument made by induced current (Figure 3 (a)-(c)).



(a) (b) (c)

(d) (e) (f)

(g)

Figure 3. Electrostatics of attrition product in the pneumatic conveying system: (a)-(c), Charges obtained by integration of induced current at an airflow rate (a) 950 L/min; (b) 1100 L/min; (c) 1600 L/min. (d)-(f), Charges obtained by integration of MPCT values at an airflow rate (d) 950 L/min; (e) 1100 L/min; (f) 1600 L/min. (g) Particle charge density (using Faraday cage) at three airflow rates.

Particle charge density

The variations of charge-to-mass ratio of particles with respect to time for the three flow patterns are presented in Figure 3(g). It can be seen that particle charge densities increase with time for all cases, which indicates a possible charge enhancement on the attrition product. On the basis of our previous work

(Yao et al. 2004), the equivalent current I_c of a granular flow system due to the motion of charge-carrying particles can be calculated by the following equation:

$$I_c = Q_p \cdot S_f \tag{1}$$

where Q_p is the particle charge density obtained using the Faraday Cage and S_f is the particle mass transported per unit time (solid flow rate). The equivalent currents calculated according to equation 1 are of the same order of magnitude as those measured using the MPCT and also as the induced currents measured using the Electrometer.

As a result, it is reasonable to conclude that as attrition progresses in the rotary valve, the electrostatics of granular flow is enhanced in the pneumatic conveying system.

Physical analysis

As stated above, granular electrostatics was quantitatively characterised by the induced current, particle charge density and equivalent current of the charged granular flow. All three measurements are found to increase in the pneumatic conveying system with granular attrition occurring in the rotary valve.

We postulate the whole charging process by the following steps. First, granular attrition produces fragments of different sizes and shapes. Some of these fragments might have sharper corners and rough surfaces than their parents and such new structures have higher charging capacity in subsequent particle-particle and particle-pipe collisions thus giving rise to particle charge enhancement. As such, the knowledge of attrition product size and shape effect on charge generation is essentially helpful to explain this phenomenon. Second, with the progress of granular attrition, the number of particles per unit weight/volume increases and this leads to more particle-particle or particle-pipe wall collisions or impactions (Smeltzer et al.[10]). As a result, there is a natural increase for charge generation of particles per unit weight/volume due to this increase in frequency. Out of these two reasons, the first one is suggested to be the more dominant one. As the dependence of particle charge generation on the particle size and shape is clearly identified, the reason why the electrostatics of granular flow increases with the occurrence of granular attrition in the rotary valve and conveying system could be uncovered consequently.

Conclusions

The electrostatics of granular flow in a pneumatic conveying system was quantitatively characterised by induced current, particle charge density and equivalent current of the charged granular flow and found to increase with granular attrition occurring in the rotary valve. As an indication of both electrostatics and hydrodynamics of granular flow, the equivalent current calculated is in good agreement with that measured in the conveying system.

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