Electrostatics of the Granular Flow in a Vertical Pneumatic Conveying System

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Abstract

The phenomenon of electrostatic charge generation in a pneumatic conveying system was studied. The main parameters used for quantitative characterization of the phenomenon included induced current, particle charge density and equivalent current of the charged granular flow. These were measured using a Digital Electrometer, Faraday Cage and Modular Parametric Current Transformer (MPCT) respectively. Three different flow patterns corresponding to the different electrostatic effects within the pneumatic conveying system were observed and these were classified as the disperse flow, half-ring flow and ring flow patterns. It was found that the induced current, particle charge density and equivalent current increased with decreasing flow rates. Electrostatic effects generally become stronger with time and this may lead to clustering behavior occurring even in the disperse flow regime.

Introduction

Pneumatic conveying systems are widely used in the energy, chemical, pharmaceutical, and material processing industries for the transportation of granular material. Solid particulate systems have a natural tendency to acquire electrostatic charges due to collisions with surfaces of a different material type (Masuda, et al. 1976). The accumulation of charges on system components may pose possible electrical hazards and lead to compromises in the safety standards of such operations. As such, a comprehensive understanding of the effects of electrostatics on the flow of granular material in a pneumatic conveying system is required.

Electrostatic effects and the associated charge generation mechanisms are complex phenomena 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 reproducibilities of experiments where such phenomena are the main focus of investigation. The amount of work reported in the literature which involves measuring or calculating electrical charges on particles in granular flow systems has also been limited due to the inherent difficulties in such investigations. Matsusaka and Masuda (2003) 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 analyzed theoretically the particle charge distribution. Al-Adel etc. (2002) examined the characteristics and extent of lateral segregation arising from static electrification in riser flows, and analyzed the steady and fully developed gas-particle flow in a vertical riser. The effects of electrostatic charge on the flow of granular material have been studied by a few research workers (Smeltzer, et al.1982, Nieh and Nguyen 1988, Gajewski 1989, Joseph and Klinzing 1983). However, flow patterns of the granular material which can arise due to such effects in a pneumatic conveying system have not been reported. Tsuji and Morikawa (1982) observed five different granular flow patterns in a horizontal conveying pipe depending on the gas-solid flow rates used but did not analyze the influence of electrostatics on these flow patterns. Based on our previous work(Rao et al., 2001, Zhu et al., 2003, 2004), it has been established that electrostatic effects play an important role in determining the flow patterns in a vertical pneumatic conveying system. This paper reports on three flow patterns observed in vertical conveying pipes which have been named disperse, half-ring and ring flow. These are believed to arise according to the relative importance between the electrostatic forces and the usual hydrodynamics forces present between the gas and solid phases. Such speculation is to be examined in the present study.

Experimental

The experimental setup used in our present study (Figure 1) was modified from the pneumatic conveying system used by Zhu et al. (2004). Solid particles are introduced into the rotary valve and entrained by air flowing from the compressor mains. The rotary valve (General Resource Corp., Hopkins, Minnesota) has 8 pockets on the rotary and rotates at 30 rpm. The inner diameter of the pipe is 40 mm and the length of the vertical pipe section between two smooth 90° elbows (R/r = 2) is about 2.97 m while the horizontal section is about 4.12 m in length. The conveying pipe is made of transparent PVC material and has a wall thickness of 5 mm. Induced current measurements were made on the vertical pipe 1.36 m away from the bottom elbow. Static (Gems, model K054205, Basingstone, England) and differential (Stellar Technology Inc., New York, Model-STI510-15G-000Stellar) pressure transducers were mounted on the vertical pipe at 1.22 and 1.49 m away from the bottom elbow. Pressure data were collected for 30 s, and the mean pressure gradients were determined for different operating conditions. One type particle as polypropylene granules (PP, density: 1123 kg/m^3, diameter: 2.8 mm) was used throughout the experiments. Visual observations of the various solid flow patterns which arise during the experiments were facilitated through the use of transparent pipes. The entire configuration was held in position using metal castings and supports with various pipe segments joined by connectors and reinforced by silicone gel.

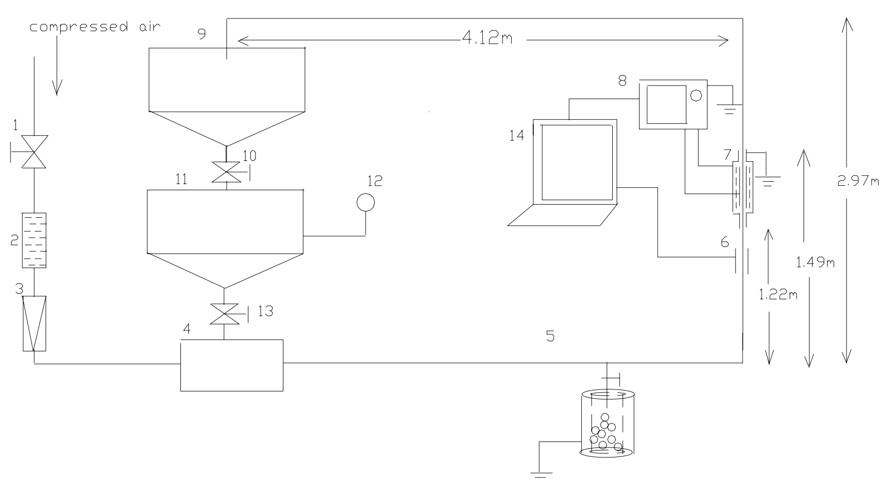


Figure 1. Schematic of the pneumatic conveying facility: 1. Air control valve, 2. air dryer (silica gel with indicator-blue), 3. rotameter, 4. rotary valve, 5. Faraday cage, 6. modular parametric current transformer , 7. induced current measurement, 8. electrometer, 9.feed recycle hopper, 10. feed control valve, 11. intermediate hopper, 12. electronic weight indicator , 13. feed control valve, 14. computer.

Air from the compressor mains (air pressure around 75 psi.) flowed through the rotary feeder, driving granules fed into the conveying system from the feed hopper. Control valves (labeled 1, 10, 13 in Figure 1.) were used to adjust the solid and air flow rates. Air flow rate was also controlled via a rotameter which allowed a maximum flow rate of 2000 liters/min. Air humidity was controlled by the dryer (silica gel with indicator-blue, labeled 2 in Figure 1) at RH = 5%. As polypropylene granules were fed back to the recycle solid hopper, they passed through a manual valve (labeled 10 in Figure 1). Closing valve 10 would enable the solid mass flow rate to be measured using the Electronic Weight Indicator (labeled 12 in Figure 1). Valve 13 was used to control the solid feed rate from the solid feed hopper into the conveying system. Ambient temperature was controlled at 28 ~ 30 °C.

During the pneumatic conveying process, collisions between the solid particles and the pipe wall generate 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 7 in Figure1). A coaxial line (connected to the high input end of an electrometer, Advantest R8252 Digital Electrometer) 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 and stored in a computer at intervals of 0.5 s. Additionally, a Modular Parametric Current Transformer (MPCT: Bergoz Instrumentation, France) which allows for current measurement with a resolution of 1 μA using a non-invasive DC beam was also used to measure the induced current (labeled 6 in Figure1). The charge density of the particles was measured by a Faraday Cage (TR8031), labeled 5 in Figure 1. 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.

Results and discussion

As mentioned in the Introduction section, the solid flow patterns observed in the vertical section of the pneumatic conveying system can be classified into the disperse flow, half-ring flow and ring flow regimes (Figure 2). The air flow rates and superficial velocities at which each flow pattern occurs and the corresponding pressure drop per unit length of pipe are shown in Table 1.

Figure 2. Three typical granular flow patterns at vertical pipe with air flow rate (a) > 1200 liters/min; (b) 900~1150 liters/min; (c) < 860 liters/min.

Table 1. Three characteristic granular flow patterns developed in a vertical conveying pipe

Experiment case	Flow pattern	Air flow rate (liters/min)	Air superficial Velocity (m/s)	Solid flow rate (g/s)	Gs (kg/m^2 s)	ΔP/L (Pa/m)
Case 1	Disperse flow	1600	21.2	44.4 ± 4.	35.3 ± 3.2	132.3
Case 2	Half-ring flow	1000	13. 3	17.4 ± 3.	13.8 ± 2.4	263.7
Case 3	Ring flow	850	11.4	10.2 ± 2.	8.1 ±1.6	518.9

Disperse flow: Air superficial velocity > 16.2 (m/s); ΔP/L <182.3 (Pa/m)
Half-ring flow: Air superficial velocity: 12. 1~15.7 (m/s); ΔP/L: 235.5~389.7 (Pa/m)
Ring flow: Air superficial velocity <11.6 (m/s); ΔP/L > 446.3 (Pa/m)

Disperse flow

When the air flow rate exceeds 1200 liters/min, particles are transported at high velocities up the vertical pipe and do not concentrate on the pipe wall. However, after a long time (about 2 hours) for the case of 1200 liters/min, some particles were found to concentrate on the pipe wall from time to time in the form of clusters (Figure 2 (a)). Due to the strong air flow, the clusters of particles seemed fairly unstable and exhibited much fluctuation in their vertical positions along the pipe. The clusters were located fairly high up in the pipe and traveled along a curved path by the pipe wall. These clusters appeared and disappeared intermittently in an unpredictable manner.

Half-ring flow

When the air flow rate is about 900 ~ 1150 liters/min, particles tend to move along curvilinear tracks in the vertical pipe. However, after about half an hour of cycling through the pneumatic conveying system, particles were observed to cluster on the side of the vertical pipe wall distant from the position of the lower horizontal pipe to form a half-annular ring structure (Figure 2(b)). This structure was located at a height of about 30 cm above the bottom elbow.

Ring flow

When the air flow rate was less than 860 liters/min, the effects of gravitational and electrostatic forces became more significant. Initially, particles slid upwards in contact with the surface of the pipe. After about 15 min, the particles were observed to travel in a spiral fashion up the vertical pipe along the pipe wall. This resulted in a ring or annulus structure with high particle concentrations adjacent to the wall and a relatively empty core region (Figure 2(c)). The structure was similarly unstable and fluctuated in its vertical position along the pipe.

At an air flow rate of 880 liters/min which was intermediate between those giving rise to the half-ring and ring flow regimes, the observed flow pattern alternated between the two characteristic half-ring and ring structures. This might be indicative of an unstable or oscillatory transition between the two flow regimes at this particular air flow rate used.

Electrostatics of granular flow in the vertical pipe

Induced current

In the experiments conducted, attempts have been made to analyze the induced current for the three types of flow described above (Figures 2). The induced current detected using the Advantest R8252 Digital Electrometer at the vertical pipe is illustrated in Figure 3 (a). It can be seen that the induced current fluctuates with time and may be negative or positive in value.

It is known that particle-wall collisions in a conveying system lead to charge generation both on the surface of the particles and the pipe wall (Masuda, et al.1976). Based on previous experiments (Zhu et al. 2003) using PP particles and PVC pipes, it can be deduced that positive charges are generated on the PP particle surface while equal amounts of negative charges are accumulated on the PVC pipe wall. At the detection segment, if particles slide on the pipe wall as in half-ring or ring flow, charges on the pipe wall are partly neutralized by those on the surface of particles and leads to a lower induced current. On the other hand, when there are no particles sliding on the pipe wall of the detection segment, charges on the pipe wall are retained, leading to a higher induced current. The charge can be modeled by the following equations:

$$q = w \cdot (\sum_{i=1}^{i=n} q_i / m_{pi}) / n = w \cdot \overline{q_m} \tag{1}$$

$$dq = \overline{q_m} \cdot dw + w \cdot d\overline{q_m} \tag{2}$$

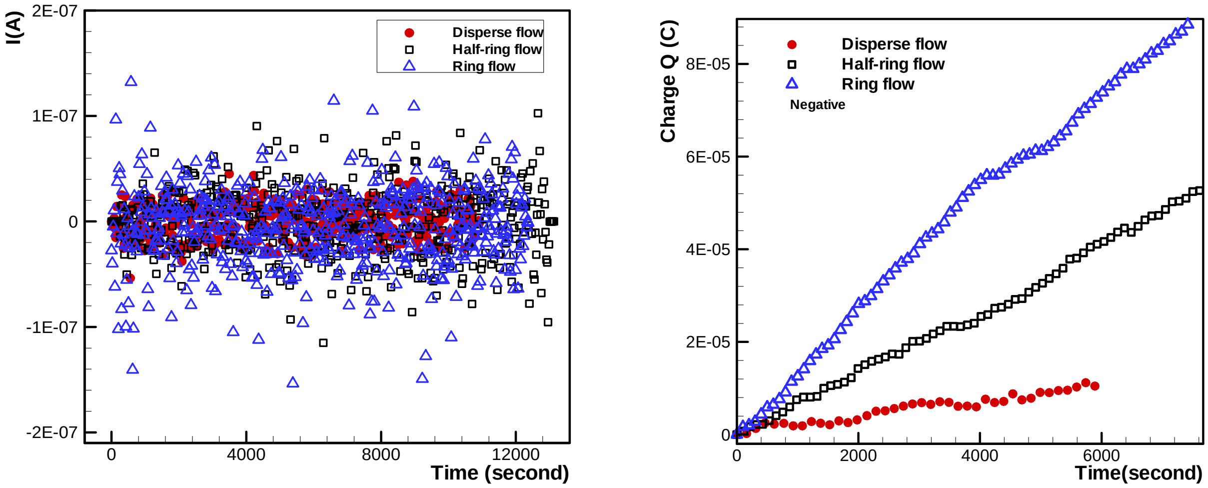
$$I = \frac{dq}{dt} = \overline{q_m} \cdot \frac{dw}{dt} + w \cdot \frac{d\overline{q_m}}{dt} \tag{3}$$

where w is the mass of particles at the detection segment, q_i is the charge of the i th particle, m_{pi} is the mass of the particle, $\overline{q_m}$ is the average charge density. Equation (1) says that the charge acquired by the electrometer from the pipe wall is equal to the product of the particle mass and the charge density at the test section. Equation (2) states that charge variation may arise due to variations in particle mass and charge density; the latter consists of the variation of the initial charge and the transferred charge between the particles and the wall. Equation (3) shows the formulation for induced current obtained by taking time differential of the previous equation. Generally, the three equations (1) ~ (3) show that the induced current is a combined effect of the solid mass flow fluctuation and the charge transferred to the pipe wall due to particle collisions. The polarity of the induced current depends on the relative magnitudes of these two effects.

From the above analysis, it can be said that the induced current measured by the Advantest R8252 Digital Electrometer is a composite value resulting from a balance between the electrostatic charges on the particle surface and pipe wall. Figure 3 shows that the magnitude of the induced current increases with decreasing flow rate. Figure 3(a) shows the values of the current sampled at a rate of 200 s^{-1}. It is evident that the current value increases with decreasing flow rate, implying enhanced electrostatics. In addition, in order to eliminate the fluctuation caused by negative and positive values, induced currents were integrated with respect to time according to equation (4) to obtain the charge Q.

$$Q = \int_0^t I dt \tag{4}$$

Figure 3 (b) shows that the charge Q detected at the detection segment increases linearly with time up to 5000 s and the rate of increase seemed constant for each of the three flow patterns. Furthermore, the magnitudes of negative currents detected were generally larger than those of positive currents, implying a net electron gain by the pipe wall.



(a) (b)

Figure 3. Comparison of the induced current acquired at the vertical pipe (a) current value for the three flows; (b) charges obtained by integration of the currents.

Particle charge density

The variations of the charge-to-mass ratio of particles with respect to time for the three types of flow are presented in Figure 4. It can be seen that particle charge densities in the half-ring and ring flow are similar with both larger than that in disperse flow. For all three cases, the particle charge density increases with time indicating a consistent accumulation of charges on the particles. This may eventually result in strong electrostatic interactions between the particles and the pipe wall and cause formation of the half-ring and ring structures described above.

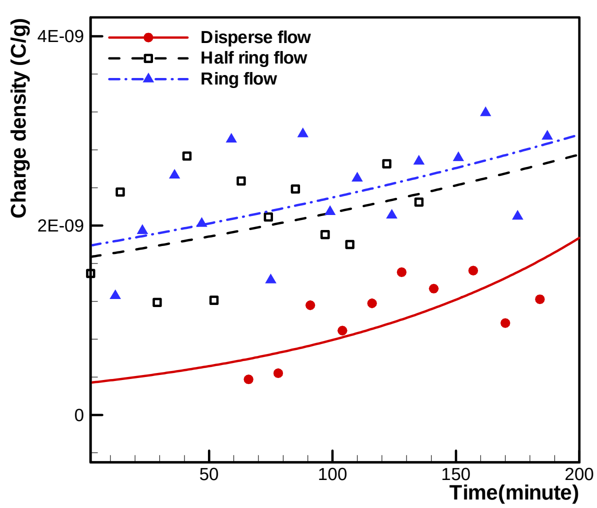


Figure 4. Comparison of particle charge density (using Faraday cage) for the three flows.

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MPCT measurements

The equivalent currents for the three flow patterns (disperse, half-ring and ring) at the vertical section of the pneumatic conveying system are presented in Figure 5 where each data point was obtained by time integration of 400 current readings from the MPCT over a time interval of 20 s using equation (4). It can be seen that MPCT values in the half-ring and ring flows are fairly similar and larger than that in disperse flow. This is consistent with the trend observed for particle charge densities for the three flow patterns discussed above (Figure 4). Furthermore, Figure 5 also suggests that particles carry positive charges while being transported along the pipe and this agrees with the contact potential difference measurements by Zhu and coworkers (Zhu et al., 2003).

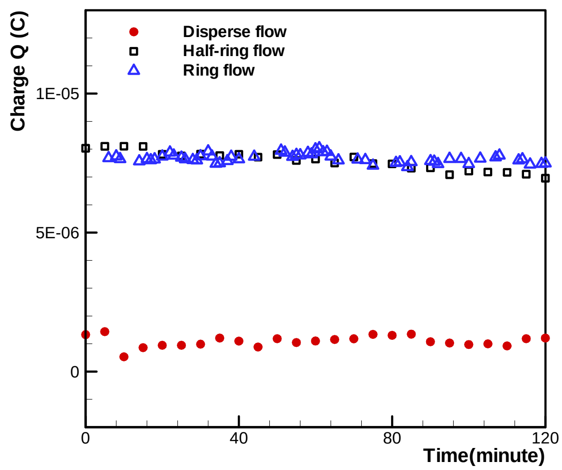

Figure 5. Comparison of charges obtained by integration of 400 MPCT value within a time interval of 20 seconds acquired at the vertical pipe for the three flows.

Conclusions

The present work can be summarized as follows. Firstly, air flow rate is the main element determining the electrostatic behavior of granular flow. The lower the air flow rate, the higher the induced current and particle charge density. These in turn lead to particle clustering and the formation of such structures as half-ring and ring in the vertical conveying pipe. Secondly, electrostatic effects increase with time. The charge accumulated at the pipe wall increases with time and the rate of increase seems constant for each of the three types of flow. Particle charge density also increases with time and this may account for clustering behavior occurring at the vertical pipe wall even when a high air flow rate is used and the dominant flow regime is that of disperse flow.

Acknowledgements

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