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On the Electrostatic Field within Space of Pipe Induced by Granular Flow in a Pneumatic Conveying System

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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[1]. 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.

Based on our previous work, it has been established that electrostatic effects play an important role in determining the granular flow behavior in the pneumatic conveying system (Rao et al.[2], Zhu et al.[3, 4]). This paper reports on electrostatic equilibrium states found in horizontal and vertical conveying pipes and at a bend section. These are believed to arise according to the relative importance between the electrostatic field strength and some particular phenomenon present in the pneumatic conveying system such as electric sparking at the bend, formation of half-ring or ring structures by granules at the vertical pipe.

Methodology

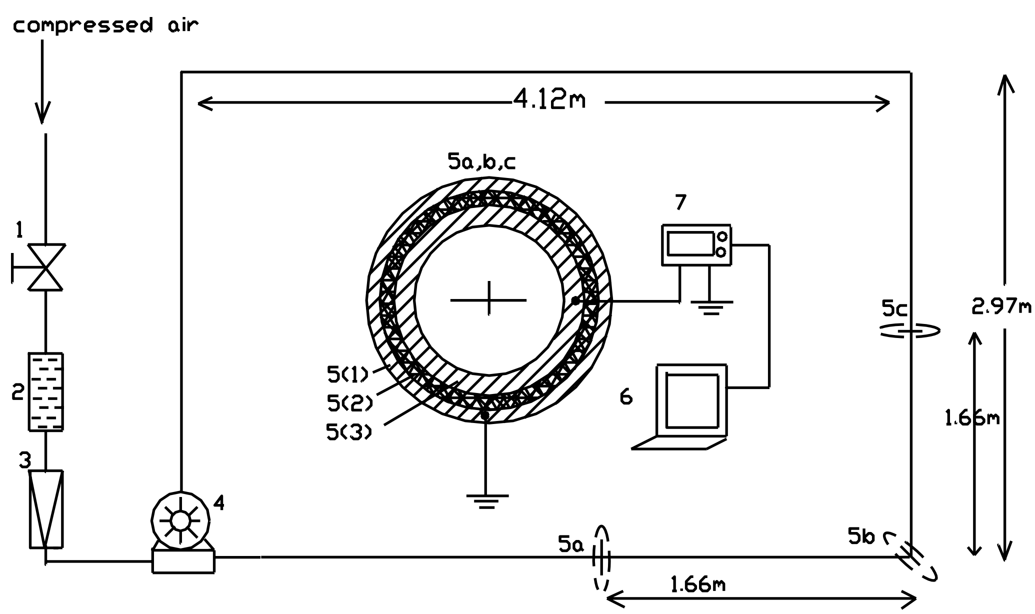


Figure 1. Experimental setup: schematic of the pneumatic conveying facility: 1. air control valve, 2. air dryer (silica gel with indicator-blue), 3. rotameter, 4. rotary valve, 5a-c. induced current measurement: (1) aluminum foil sheet (0.07mm); (2) polymer film (0.04mm); (3) aluminum foil sheet (0.07mm), 6. computer, 7.electrometer.

The experimental setup used is shown in Figure 1. Solid granules 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 (bend curvature: 2) is 2.97 m, while the horizontal section is 4.12 m in length. The conveying pipe is made of PVC that is transparent, to allow visual observation and has a wall thickness of 5 mm. Induced current measurements (Figure 1, 5: a, b, c) were made at both the horizontal and vertical pipe 1.66 m away from the elbow. 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. Polypropylene granule (PP, diameter 2.8 mm, bulk density 1123 kg/m^3) was used throughout the experiments.

Air from the compressor mains (air pressure: 75 psi) flowed through the rotary feeder, driving granules fed into the conveying system. A valve (Figure 1, 1) was used to adjust the air flow rate. The air flow rate was also controlled via a rotameter (3) which allowed a maximum flow rate of 2000 L/min. Based on previous work (Yao et al.[5]) three air flow rates were chosen: 1600, 1100 and 950 L/min, and the corresponding air superficial velocity inside the pipe was 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. For the three air flow rates of 1600, 1100 and 950 L/min, the corresponding solid flow rate was measured as 40.67, 21.87 and 14.50 g/s.

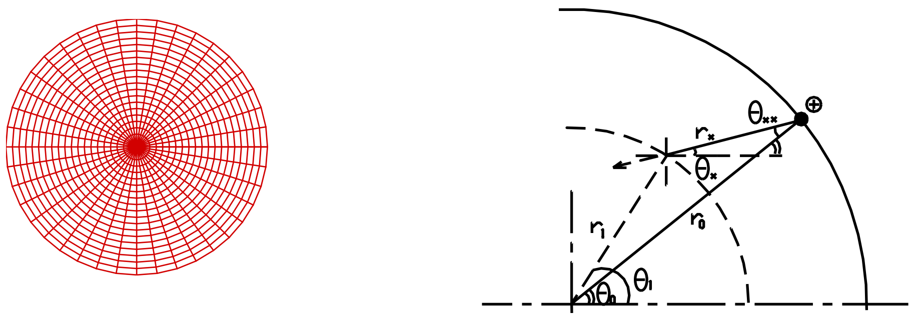
During the pneumatic conveying process, collisions between the solid granules and the pipe wall generate electrostatic charges. The current induced along the surface of the pipe wall as a result of these charges was measured as a function of time. This was done by wrapping an aluminum foil sheet tightly over the outer wall of the PVC pipe (Figure1, 5 (1)-(3)). A coaxial line (connected to the high input end of an electrometer (7), 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.

Electrostatic field calculation

The electrostatic field of a point charge at the cross section of a pipe (Figure 2 (a)) can be modeled by the following equation (Halliday et al. [6]).

$$e = \frac{1}{4\pi\varepsilon_0} \cdot \frac{q}{{r_x}^2} \tag{1}$$

where ε_0 is permittivity constant (in vacuum 8.85 $\times 10^{-12}$ $C^2 / N \cdot m^2$), r_x is the distance from the point charge, q is the point charge.



(a) (b)

Figure 2. Electrostatic field calculation: (a) simulation grid (20×40); (b) the electrostatic field vector at one point (r_1, θ_1) due to a positive point charge (r_0, θ_0).

In the triangle (shown in Figure 2(b)) formed by three points: charge point (r_0, θ_0), object point (r_1, θ_1) and the field center (0, 0), the distance r_x between the charge point and the object point can be calculated using the cosine rule:

$${r_x}^2 = {r_1}^2 + {r_0}^2 - 2 \cdot r_1 \cdot r_0 \cdot \cos(\theta_0 - \theta_1) \tag{2}$$

where r_0, θ_0 is the radius and radian of the charge point respectively, r_1, θ_1 is the radius and radian of the object point respectively.

The direction of the electrostatic field vector at the object point (r_1, θ_1) from the point charge (r_0, θ_0) can be calculated by equation (3) using the sine rule in this triangle.

$$\frac{r_x}{\sin|\theta_0 - \theta_1|} = \frac{r_1}{\sin\theta_{xx}}$$

$$\theta_{xx} = \arcsin\left(\frac{r_1 \cdot \sin|\theta_0 - \theta_1|}{r_x}\right) \tag{3}$$

$$\theta_x = \theta_0 - \theta_{xx}$$

where θ_{xx} is the angle between the direction of the electrostatic field vector and that of the charge point to the field center, θ_x is the angle between the direction of the electrostatic field vector and the x- axis. So, the electrostatic field vector in the x- and y- direction can be obtained by:

$$e_x = e \cdot \cos\theta_x = \frac{1}{4\pi\varepsilon_0} \cdot \frac{q}{{r_x}^2} \cdot \cos\theta_x;$$

$$e_y = e \cdot \sin\theta_x = \frac{1}{4\pi\varepsilon_0} \cdot \frac{q}{r_x^2} \cdot \sin\theta_x \tag{4}$$

In a two-dimension field, the electrostatic field generated by a point charge *q* at the point (*i, j*) can be calculated:

$$e_{x(i,j)} = \frac{1}{4\pi\varepsilon_0} \cdot \frac{q}{r^2{}_{x(i,j)}} \cdot \cos\theta_{x(i,j)}$$

$$e_{y(i,j)} = \frac{1}{4\pi\varepsilon_0} \cdot \frac{q}{r^2{}_{x(i,j)}} \cdot \sin\theta_{x(i,j)} \tag{5}$$

In the pneumatic conveying system, based on previous experiments (Zhu et al.[4], Yao et al.[5]) using PP granules and PVC pipes, it can be deduced that positive charges are generated on the PP granule surface while equal amounts of negative charges are accumulated on the PVC pipe wall. The electrostatic field vector at the point (*i, j)* from a point charge at (*l, k*) can be calculated by the following equations:

$$e_{x(l,k,i,j)} = \frac{1}{4\pi\varepsilon_0} \cdot \frac{q_{(l,k)}}{r^2{}_{x(l,k,i,j)}} \cdot \cos\theta_{x(l,k,i,j)} \tag{6}$$

$$e_{y(l,k,i,j)} = \frac{1}{4\pi\varepsilon_0} \cdot \frac{q_{(l,k)}}{r^2{}_{x(l,k,i,j)}} \cdot \sin\theta_{x(l,k,i,j)}$$

From all point charges in the cross section, the general electrostatic field at the point (*i, j*) can be integrated as:

$$E_{x(i,j)} = \sum_{l=1}^{m}\sum_{k=1}^{n}\ \sum_{i=1}^{m}\sum_{j=1}^{n} e_{x(l,k,i,j)} = \sum_{l=1}^{m}\sum_{k=1}^{n}\ \sum_{i=1}^{m}\sum_{j=1}^{n} \frac{1}{4\pi\varepsilon_0} \cdot \frac{q_{(l,k)}}{r^2{}_{x(l,k,i,j)}} \cdot \cos\theta_{x(l,k,i,j)}$$

$$E_{y(i,j)} = \sum_{l=1}^{m}\sum_{k=1}^{n}\ \sum_{i=1}^{m}\sum_{j=1}^{n} e_{y(l,k,i,j)} = \sum_{l=1}^{m}\sum_{k=1}^{n}\ \sum_{i=1}^{m}\sum_{j=1}^{n} \frac{1}{4\pi\varepsilon_0} \cdot \frac{q_{(l,k)}}{r^2{}_{x(l,k,i,j)}} \cdot \sin\theta_{x(l,k,i,j)} \tag{7}$$

The magnitude of the electrostatic field vector at point (*i, j*) can be finally obtained:

$$E_{(i,j)} = \sqrt{E^2{}_{x(i,j)} + E^2_{y(i,j)}} \tag{8}$$

Results and analysis

Averaged current

In this work, induced current at three air flow rates were measured in the pneumatic conveying system. The induced current is supposedly determined by three factors: first, the charges on the pipe wall; second, the charged granules passing through the detection segment without contacting the pipe wall; third, the charging effect of granules which are in contact with the pipe wall due to impacts or through sliding, rolling and so on. In reality, the second factor is negligible in causing charge generation either on the pipe wall or granules. This can be explained as follows. When a charged granule approaches the detection segment, a quantity of charge equal to that carried by the granule is induced on the detection segment; when the granule departs from the segment, these induced charges are discharged. Thus, there is no net charge generated during the process.

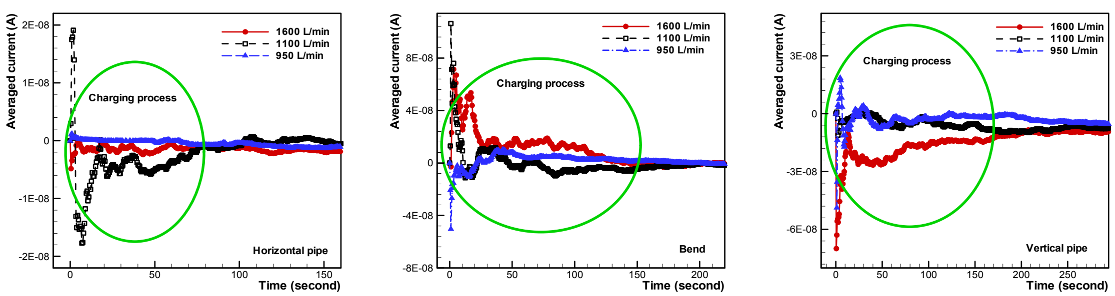
To eliminate this factor, a concept of averaged current is proposed:

$$\bar{I} = \frac{1}{T}\int_0^T I \cdot dt \qquad (9)$$

where *I* is the induced current acquired from the electrometer, *T* is the time period.

In our previous work (Yao et al.[5]), the polarity of the induced current generated in the conveying system was found to fluctuate over both negative and positive values and the mechanism was explained. Here, the averaged current according to equation (9) at the three pipe sections is shown in Figure 3. It is seen that, for all cases, the averaged current does reach a constant negative value over a period of time. This result seems reasonable because negative charges were found to be generated at the pipe wall by granule-wall collisions (PP-PVC interacts) (Zhu et al.[4], Yao et al.[5]). The attainment of a steady averaged current indicates an “electrostatic equilibrium state”.

Charging process



(a) (b) (c)

Figure 3. Charging process at three pipe sections: (a) horizontal; (b) bend; (c) vertical.

Figure 3 shows that for all cases studied, the averaged current did undergo a transient state before reaching the state of electrostatic equilibrium and the time taken to reach such a steady state varies with air flow rate and the specific pipe section. To facilitate the study of such a “charging process”, a ratio of instantaneous averaged current to the final steady state value is defined as follows:

$$DI_{(i)} = \frac{\bar{I}_{(i)}}{\bar{I}_0} \qquad (10)$$

where $DI_{(i)}$ is the ratio of the averaged current at the i^{th} moment to the constant value, $\bar{I}_{(i)}$ is the averaged current at the i^{th} moment and $\bar{I}_0$ is the constant averaged current. In this work, $\bar{I}_0$ is assumed to be equal to the value of $\bar{I}_{(i)}$ at the end of the experiment.

In addition, charges generated on the pipe wall over a period of time T can be calculated as:

$$Q = \int_0^T I \cdot dt \tag{11}$$

Here, the electrostatic equilibrium state is assumed to be reached when $DI_{(i)}$ is less than or about 0.1. The various quantities obtained at equilibrium for all cases are summarized in Table 1. It shows that in the pneumatic conveying system, the higher the air flow rate the shorter the charging process. Such a trend is observed for all three pipe sections (horizontal, vertical and bend) considered. Furthermore, regardless of the air flow rate used, the horizontal pipe section reached equilibrium in the shortest time. This was followed by the vertical pipe section while the bend section took the longest time to reach equilibrium. Except at the bend section, charges generated at the pipe wall at equilibrium increase with the length of the charging process. For the bend section, the highest charge generated occurs at the highest air flow rate.

Table 1. The electrostatic equilibrium state of granular flow in the pneumatic conveying system

Pipe section	Air flow rate (L/min)	t_i (s)	$DI_{(i)}$	$\bar{I}_{(i)}$ (A)	Charge Q (C)	Pipe wall linear charge density λ (C/m)
Horizontal	1600	9.01	1.17E-01	-1.85E-09	-1.66E-08	-1.32e-07
Horizontal	1100	36.09	1.05E-01	-3.10E-09	-1.12E-07	-8.89e-07
Horizontal	950	663.88	4.99E-02	-3.07E-10	-2.04E-07	-1.62e-06
Vertical	1600	12.52	3.63E-02	-1.15E-08	-1.44E-07	-1.14e-06
Vertical	1100	60.31	9.33E-03	-6.82E-09	-4.11E-07	-3.27e-06
Vertical	950	1019.58	7.52E-02	-1.94E-09	-1.98E-06	-1.57e-05
Bend	1600	917.97	8.54E-02	-2.85E-09	-2.61E-06	-2.08E-05
Bend	1100	1132.57	7.34E-02	-6.59E-10	-7.46E-07	-5.93e-06
Bend	950	1756.13	9.99E-02	2.86E-10	5.02E-07	3.99e-06

Physical analysis of the electrostatic equilibrium state in the pneumatic conveying system

It is known that granule-wall collisions in a conveying system lead to charge generation both on the surface of the granules and the pipe wall (Masuda et al.[1]). Such processes can be seen as giving rise to the charging effect. On the other hand, if granules and pipe wall were initially charged, charges on the surface of granules will be partly neutralized by those on the pipe wall during granule-wall collisions. This can be seen as a discharging process. At the start of the pneumatic conveying experiments, granules and pipe wall were fairly fresh and carrying few charges so that they were easily charged by granule-wall collisions. This gave rise to the charging process. After a certain length of time, charges accumulated on granules and the pipe wall and the discharging effect became more significant. As the charging/discharging process reached an equilibrium state, the amount of charges on granules and the pipe wall became steady, thus attaining the "electrostatic equilibrium state" mentioned above. It is known that such equilibrium is actually a "dynamic equilibrium". In the conveying system there may be many factors affecting the electrostatic equilibrium state, such as air flow rate, solid flow rate, air pressure, air humidity, granule characteristics (size, shape, density, material etc.) and so on. In the experiments, the electrostatic equilibrium state was also found to be different at different pipe sections in the conveying system.

From the above analysis (Figure 3), it is said that high air flow rate will shorten the period to reach the electrostatic equilibrium state in the conveying system. It can be explained by the higher frequency of granule-wall collisions at high air flow rates which leads to a higher efficiency for the process of charging and discharging to reach the equilibrium state.

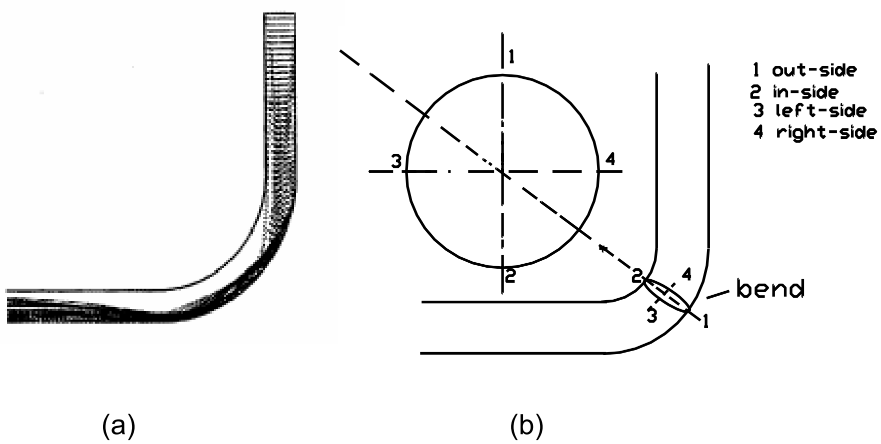


Figure 4. Particle-wall collisions at the 90° bend: (a) particles trajectory throughout the bend from vertical to horizontal (Fan et al.[7]): particle diameter 20 ~80 *μm*, air flow rate 500 L/min, fluid average velocity 41.2 m/s, bend curvature 3; (b) schematic of the bend.

In the conveying system, granules encounter the largest amount of granule-wall collisions at the bend (90°) (illustrated in Figure 4) where their trajectories are rather complex. In former works (Fan et al.[7], Lee et al.[8]), it was found that most particle-bend impacts occur on the outer wall (in Figure 4 (b)) while less occur on the left- and right-wall and the least on the inner wall. So, it is reasonable to believe that charge generation due to granule-wall collisions will be non-uniform at the bend. This is why it takes the bend the longest period to reach the electrostatic equilibrium state in the conveying system as shown in Table 1. By the same reasoning, granular flow in the vertical pipe was found (Rao et al.[2], Zhu et al. [3, 9]) to be more complex than that at the horizontal pipe so that it takes more time for the former to reach the electrostatic equilibrium state. This statement can also be verified from Table 1. Hence, it can be deduced that the electrostatic equilibrium state involving granule-wall collisions shows high reliance on the granules behavior and local flow characteristics (such as fluid turbulence): the more complex the granular flow the longer to reach the electrostatic equilibrium state.

In general, it is believed that a long period to reach the electrostatic equilibrium state does cause high charge accumulation at the pipe wall. This applies to the present experiments conducted at both vertical and horizontal pipe sections as summarized in Table 1. However, it does not apply to the bend. This may be due to a hydrodynamic dependent property of granules at the bend and shows that more work is needed on this aspect.

Electrostatic field

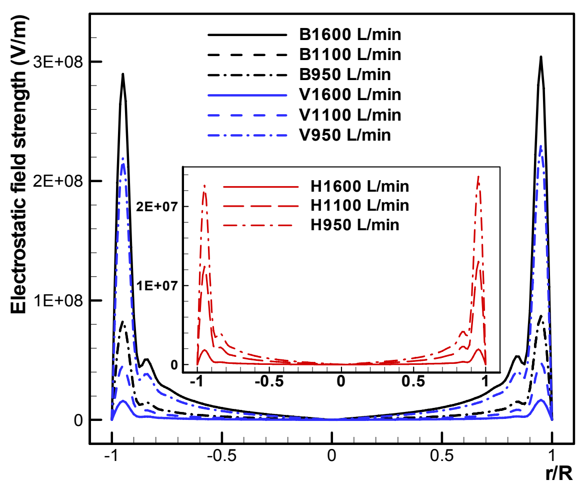


Figure 5. Radial distribution of the electrostatic field strength from the charged pipe wall at the electrostatic equilibrium state. (H: horizontal pipe; B: bend; V: vertical pipe)

As the electrostatic equilibrium state is set up, it is possible to evaluate the electrostatic field strength in the pneumatic conveying system. According to equation (1)-(8), the electrostatic field strength from the charged wall was calculated for the three pipe sections: horizontal, bend and vertical. The results are shown in Figure 5, where the charges are assumed to distribute equally around the pipe wall. It is seen that, for all cases, the highest electrostatic field strength appears near the pipe wall and degrades from the pipe wall to the pipe center. In the conveying system, the highest strength occurs at the bend (Figure 5), which is independent of air flow rate. For the horizontal pipe and vertical pipe, the electrostatic field strength increases with decreasing air flow rate. However, for the bend, the highest field strength occurs at the highest air flow rate. Basically, the electrostatic field strength in the conveying system is characterized by the amount of charges accumulated at the pipe wall at the electrostatic equilibrium state. The larger the amount of charges accumulated, the higher the electrostatic field strength achieved.

The results achieved above can help to explain the phenomenon of electric sparking occurring in a pneumatic conveying system. It was found that electric sparking tended to occur at the bend at high air flow rates.

Conclusions

According to the averaged current defined, it is found that there is a "charging process" and an "electrostatic equilibrium state" for all cases conducted in the pneumatic conveying system. High air flow rate will shorten the charging process. In the pneumatic conveying system, the sequence of reaching the electrostatic equilibrium state from fastest to slowest is: horizontal, vertical and bend. The length of the charging process may determine the amount of charges accumulated at the electrostatic equilibrium state. From the experiments, it is deduced that the electrostatic equilibrium state involving granule-wall collisions shows high reliance on the granular behavior and local flow characteristics: the more complex the granular flow the longer the time taken to reach the electrostatic equilibrium state.

The electrostatic field strength is evaluated for the charged pipe wall in the conveying system. The highest electrostatic field strength appears near the pipe wall and degrades from the pipe wall to the pipe center. In the conveying system, the highest electrostatic field strength is found at the bend. For the horizontal pipe and vertical pipe, the electrostatic field strength increases with decreasing air flow rate. However, for the bend, the highest electrostatic field strength occurs at the highest air flow rate. Basically, the electrostatic field strength from the charges at the pipe wall is characterized by the amount of charges accumulated at the electrostatic equilibrium state, the large the amount of charges accumulated, the higher the electrostatic field strength achieved.

Acknowledgements

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