EFFECT OF ELECTROSTATIC CHARGE ON HYDRODYNAMICS OF GAS-SOLID FLUIDIZED BEDS

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Abstract-The aim of this work was to investigate the effect of accumulation of electrostatic charge on hydrodynamics of gas-solid fluidized beds. Experiments were performed to evaluate the influence of generated electrostatic charge on hydrodynamic parameters such as minimum fluidization velocity and transition velocity from bubbling to turbulent fluidization. Experiments were carried out with adding anti-static agent to the bed in order to study the hydrodynamics of a bed of uncharged particles. Comparing results of experiments with anti-static agent in comparison with charged particles revealed that the minimum fluidization velocity increases with charge accumulation. Based on the standard deviation of pressure fluctuations, it was found that the transition velocity to turbulent fluidization decreases significantly with the electrostatic charge on particles. Effect of electrostatic charge on fluidization parameters is considerable for particles with mean diameter of 460-600 µm.

INTRODUCTION

Gas-solid fluidized beds are widely used in industrial processes due to their efficient solids circulation and mixing. Generation and accumulation of electrostatic charge in a gas-solid fluidized bed occurs during particle-particle and particle-column wall frictions. Consequently, accumulation of electrostatic charge in fluidized beds is unavoidable which can interfere with the bed hydrodynamics, bubble size and shape, particle mixing rate and fines elutriation (Hendrickson, 2006). Besides, generation and accumulation of charge would cause harsh operational conditions such as particle agglomeration, regular shut down for clean-up the created wall sheeting, production losses and additional maintenance costs (Mehrani et al., 2005; Sowinski et al., 2012; Giffin et al., 2013; Song et al., 2016). Thus, reducing the charge accumulation in the reactor is important from the economical point of view.

There are various methods for reducing charge accumulation such as surface pretreatment (Park et al., 2002), increasing relative humidity (Mehrani et al., 2007a; Demirbas et al., 2008; Giffin et al., 2013), addition of fines (Mehrani et al., 2007b; Mehrani et al., 2007a; Moughrabiah et al., 2012) and electrostatic elimination with corona discharging (Revel et al., 2003). Most of the above mentioned methods are not applicable to industrial fluidized beds because of limitations in material of wall and particles and operating conditions (Dong et al., 2014). These methods may cause other problems such as increase in the agglomeration rate, reduction of particles surface activity, changes in the hydrodynamics and surface reactions (Hendrickson, 2006). So far, the most applicable method for reducing charge accumulation in a fluidized bed is addition of anti-static agents which operates by increasing charge dissipation (Matsusaka and Masuda 2003; Zhou et al., 2013).

Although, minimum fluidization velocity and velocity of onset of turbulent fluidization are key parameter in fluidization processes, effect of electrostatic change of particles on these parameters has not been investigated properly. In the present study, pressure fluctuation measurement was used as the most common method to characterize the fluidized bed hydrodynamic (van Oment et al., 2011, He et al., 2015). Experiments were performed with adding anti-static agent to the bed in order to study the hydrodynamics of a bed of uncharged particles. Minimum fluidization velocity and transition velocity from bubbling to turbulent fluidization were evaluated based on pressure drop and pressure fluctuations. Comparing results of experiments with uncharged and charged particles as well as with calculated values leaded to a better understanding of the influence electrostatic charge of particles on fluidized bed hydrodynamics.

EXPERIMENTAL

Experiments were performed in a cylindrical fluidized bed made of glass with inner diameter of 26 mm and height of 800 mm (Fig. 1). A particle sampling port, inclined downward at 45° to the vertical axis, was located at the same height of the pressure probe, almost 2.5 cm above the distributor, on the opposite face of the bed.

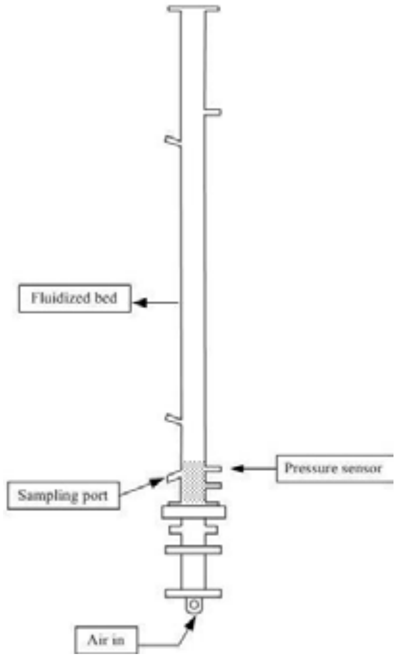

Fig. 1. Schematic of the experimental apparatus.

Air was supplied by a compressor into a buffer tank and then into a dryer. In the dryer, the relative humidity of air was limited by adjusting the operational pressure and temperature. Air flow rate was controlled by a mass flow controller. All experiments were performed at room temperature.

Polyethylene particles with particle density of 0.94 g/cm^3 were used in the experiments. The sieved particles had a relatively narrow size distribution with mean diameter of 275, 460 and 1000μm. Polyethylene particles coated by anti-static material were added to the bed (10% by mass) to neutralize the charge of particles.

Before each experiment, 3 steps were followed to prepare the column for the test. First, the column was cleaned and purged with dry air to remove any particles remained from the previous test. Second, the column was grounded for 24 hours to remove any accumulated electric charge remained on the column wall since the previous experiment. Third, the column was swept with the fluidization air to assure that temperature and relative humidity are almost constant. Before each test with charged particles, in addition to the 3 steps, particle charging step was performed. For this purpose, particles were poured into the column and fluidized at ~$3U_{mf}$ for an hour. During the fluidization, particle-wall and particle-particle contacts generate electrostatic charge in the column. Strong particle motion in the bed assures that particles are charged to the saturated level. The saturated charge level is the maximum charge accumulation in the column during fluidization (Giffin et al., 2010; Jalalinejad et al., 2015; He et al., 2016; Zhang et al., 2016).

Pressure fluctuations were measured to characterize the fluidized bed hydrodynamic. A pressure probe (model SEN-3248 (B075), Kobold Company) with a response time of less than 1 ms was screwed onto the wall at 4 cm above the distributor. The sampling frequency of 400 Hz was used to acquire the pressure fluctuations in the fluidized bed (Johnsson et al., 2000). Charge of particles was measured by the Faraday cage method. The Faraday cup consists of a double layer cylinder separated by electrical insulating foam, with the inner layer connected to an electrometer. The electrometer (Monroe Electronic, Nano Coulomb Meter 284) has the standard measuring range of 0-200 nC. At the startup of the tests with charged particles, after the charging step, samples of particles were taken from the bed and poured into the cup to measure the charge to mass ratio of particles.

RESULTS AND DISCUSSION

Saturated level for charged particles

As was mentioned before, the bed was fluidized at $3U_{mf}$ for an hour prior to any measurement to assure that the particles are charged to the saturated level. The ratio of total charge of particles to their mass at the saturated level is reported in Table 1. The results indicate that the charge generation increases with increasing the particle size. This trend is in agreement with the results reported by Guardilio et al. (1996).

Table. 1. Total charge to mass ratio of particles

d_p (mm)	q/m (nC/g)
0.275	-4.1
0.460	-5.5
0.600	-6.4

Weight of particles increase with their size, thus their contacts and collisions become more energetic. This increases the charge transfer due to particle-wall and particle-particle contacts. These energetic collisions of particles increases the total charge accumulation in the bed.

Minimum fluidization velocity

Minimum fluidization velocity is defined as the superficial velocity at which the whole particles begin to become fluidized. This velocity is usually determined experimentally by measuring the pressure drop as a function of gas velocity. Curves of pressure drop vs. air velocity for fluidized beds of charged and uncharged particles are shown in Fig. 2. This figure demonstrates that the minimum fluidization velocity of a bed of charged particles is higher than that of uncharged particles. Also, the pressure drop of in the bed of charged particles exhibits an overshoot at the minimum fluidization velocity which increases by increasing the charge accumulation.

During fluidization, charge transfer occurs when particles hit the neutral bed wall. In triboelectric series, glass is placed higher than polyethylene. Therefore, during particle-wall contacts, particles are negatively charged and the column wall is charged positively (Diaz and Navarro, 200These4). As the negatively charged particles move toward the distributor, the attractive force to the oppositely charged wall and repulsion from other particles (far from the wall) would prevent the movement of particles toward center of column. Therefore, a dense and stagnant region was created near the wall. At low velocities, motion of bubbles is not strong enough to enable the bubble to penetrate into the dense region. As the gas velocity increases, strong motion of bubbles detaches some layers from the resistive zone and decreases the size of the static zone. Therefore, in the bed of charged particles, at the minimum fluidization velocity, the drag force should overcome not only the total weight but also the electrostatic force of charged particles. Electrostatic force between charged dielectric particles (with low charge dissipation) is relatively strong and can be of the same order as the gravitational force. Such a strong force can affect the force balance on particles and the required drag force for fluidization of particles. Since polyethylene has a high saturated level of electrostatic charge, the corresponding electrostatic force in the column is high which affects the minimum fluidization velocity. Thus, as can be seen in Fig. 2 in the case of charged particles, fluidization starts at a higher velocity and the minimum fluidization velocity increases by increasing charge accumulation.

In experiments with charged particles, when the gas flow was stopped, a thick layer of particles attached to the wall was observed. This layer reduces the total weight of particles in the fluidized part of the bed which leads to a lower pressure drop of the mass of particles in the column. As it can be seen in Fig. 2, the final pressure drop of the bed of charged particles is higher than that of uncharged particles.

Minimum fluidization velocities obtained from Fig. 2 as well as the velocities calculated based on the equation of Wen and Yu (1966) are shown in Fig. 3. This figure shows that the difference between velocities corresponding to charged and uncharged particles and their deviation from the correlation increases with increasing the particle size.

Electrostatic charge of particles increases with particle size (Guardilio et al., 1996), thus, its effect on the minimum fluidization velocity is stronger for a bed of larger particles. High electrostatic force creates a thick layer of attached particles on the column wall. After fluidization, at the startup of the charged runs, the layer of particles can be observed as they are adhered to the column wall. This layer is strongly attached to the wall in the bed of 600 µm particles compared with smaller particles. Therefore, as shown in Fig. 3, for particle size of 600 µm, higher difference between the minimum fluidization velocities of charged and uncharged particles is observed. The overshoot in the case of charged particles of larger particles (see Fig. 2) is another indication of increasing the inter-particle force by increasing the particle size.

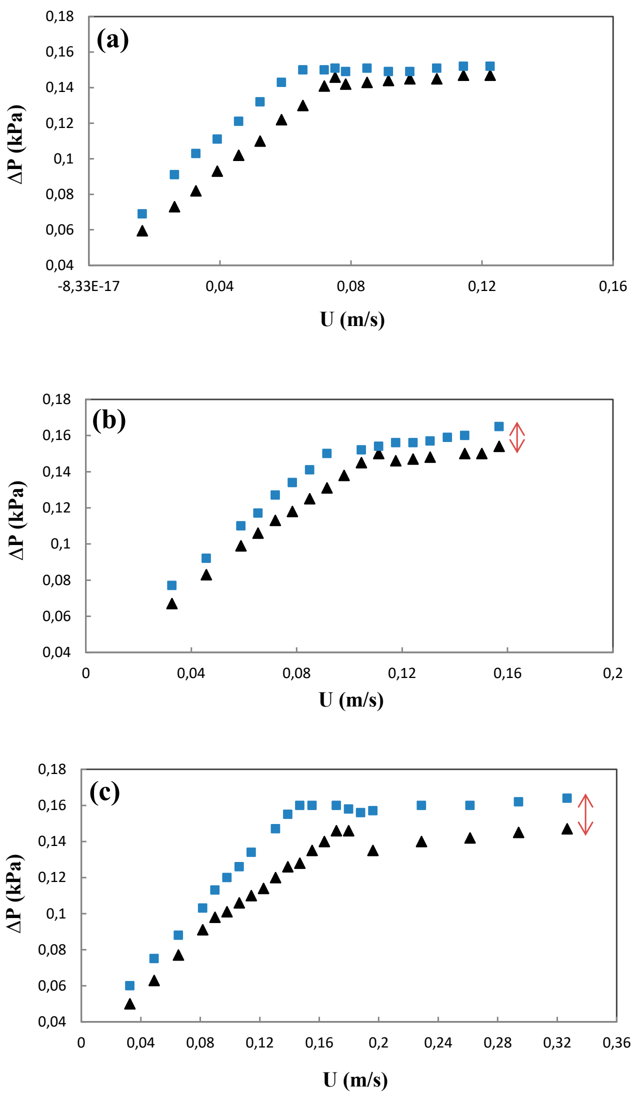

Fig. 2. Pressure drop as a function of gas velocity in beds of various particle size, (a) d_p=0.275 mm, (b) d_p=0.460 mm, (c) d_p=0.600 mm: charged particles (▲) and uncharged particles (■)

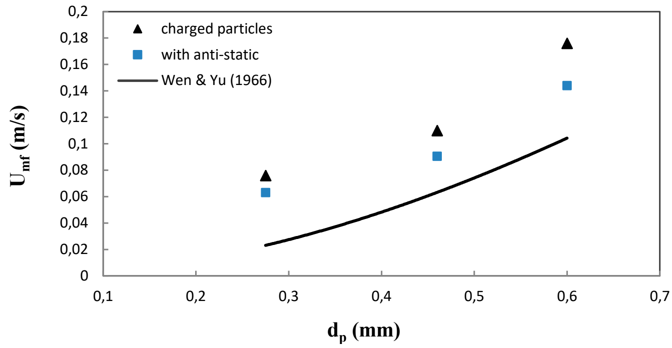

Fig. 3. Calculated and experimental minimum fluidization velocities for beds of charged particles and the bed containing anti-static agent.

Correlations for estimating the minimum fluidization velocity, such as Wen-Yu (1966), have been developed for situations where inter-particle forces are negligible and the gravity is the only force that resists fluidization of particles. In such cases, the pressure drop of bed at minimum fluidization velocity is equal to the total weight of particles per unit bed area. Obviously, the existing correlations may not be suitable for beds with strong inter-particle forces. Fig. 3 shows that the deviation of experimental results from the correlation results increase with increasing the charge of particles.

Minimum fluidization velocity in the bed of uncharged particles is closer to the correlation compared to the charged ones. Therefore, it can be concluded that the correlation predicts minimum fluidization velocity correctly for beds with low electrostatic charge accumulation.

Transition to turbulent fluidization

Turbulent fluidization regime occurs between bubbling and fast fluidization regimes. In this work, the velocity at the onset of turbulent fluidization was determined to be the superficial gas velocity at which maximum of standard deviation of pressure fluctuations were observed. Fig. 4 shows the standard deviation of pressure fluctuations as a function of superficial gas velocity for charged and uncharged particles. In the bubbling regime, the standard deviation of pressure fluctuations increase with gas velocity. Comparing with the uncharged particles results, the charged curve reaches the maximum standard deviation of pressure fluctuations at a lower velocity. This means that the transition to turbulent fluidization is delayed when particles are electrostatically charged.

As discussed previously, attraction between column wall and charged particles creates a packed region near the wall. The packed layer causes the side bubbles to change direction toward the center of the bed to pass through the lower resistant part of the column. This change of direction towards the center leads to faster coalescence of bubbles compared to uncharged particles result.

The correlation of Bi and Grace (1995) gives the best prediction of the transition velocity to turbulent fluidization when measuring absolute pressure fluctuations. The experimental transition velocities on this work and those calculated from the correlation of Bi and Grace (1995) are shown in Fig. 5. As can be seen in this figure, the deviation between experimental results and the correlation increases with increasing the charge of particles. Therefore, the correlation of Bi and Grace (1995) is not suitable for beds of particles with strong inter-particle forces.

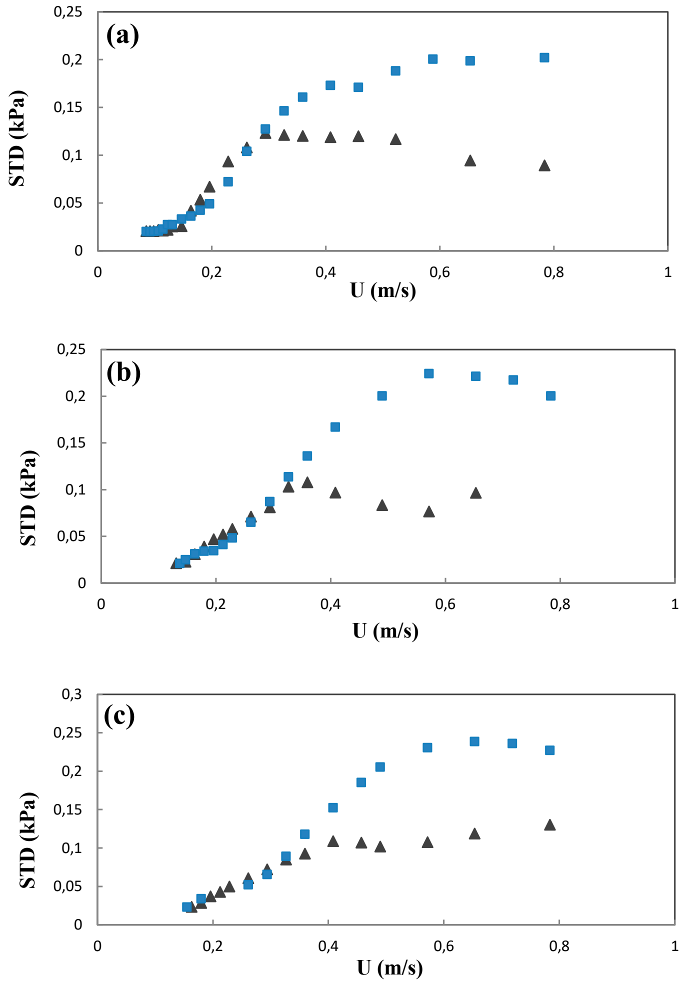

Fig. 4. Standard deviation of pressure fluctuations as a function of superficial gas velocity, (a) d_p=0.275 mm, (b) d_p=0.460 mm, (c) d_p=0.600 mm: charged particles (▲) and uncharged particles (■)

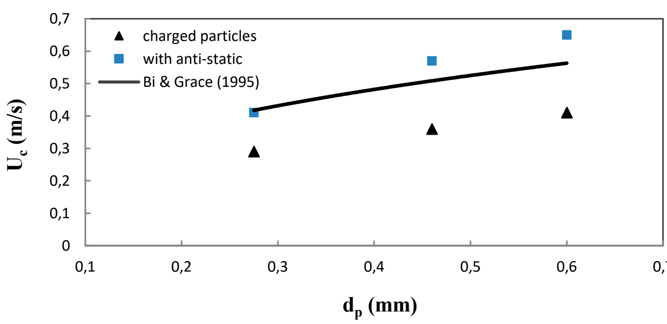

Fig. 5. Calculated and experimental transition velocities to for beds of charged particles and the bed containing anti-static agent.

CONCLUSION

In this study, effect of electric charge accumulation in a fluidized bed on the hydrodynamic parameters was investigated. Triboelectric charge generation in fluidized beds is unavoidable due to vigorous mixing of particles. In order to resemble uncharged system, anti-static agent was added to the bed. In the experiments, particles coated with anti-static were used as uncharged particles. Using uncharged particles resulted in reduction of charge accumulation and the related electrostatic forces in the bed.

Comparing the results of charged and uncharged particles revealed that the minimum fluidization velocity increases with increasing the electric charge accumulation in the bed. As the negatively charged particles move toward the distributor, the attractive electrostatic force to the oppositely charged wall would prevent the movement of particles toward the center of column and divides the bed into two zones: a static layer attached to the wall which consists of highly charged particles, and a core zone in which electrostatic charge of particles is less. Therefore, in the bed of charged particles, at the minimum fluidization velocity, the drag force should overcome not only the total weight but also detach the static layer which is the reason for observing a higer minimum fluidization velocity. As charge generation increases with the particle size, the difference between minimum fluidization velocities of from charged and uncharged beds increases with increasing the particle size.

Standard deviation of pressure fluctuations were used to determine transition to turbulent fluidization. It was found that the transition velocity decreases with increasing the electrostatic charge of particles. The above mentioned dense zone of charged particles causes the side bubbles to change direction toward the center of the column which leads to faster coalescence of bubbles compared to the bed of uncharged particles.

NOTATION

d_p particle diameter, mm
P pressure, kPa
q/m charge to mass ratio, nC/g
STD standard deviation of pressure fluctuations, kPa
U superficial gas velocity, m/s
U_c transition velocity to turbulent fluidization, m/s
U_{mf} minimum fluidization velocity, m/s

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