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Experimental Studies on a Swirling Fluidized Bed with Annular Distributor

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Abstract: This study reports the experimental findings on a swirling fluidized bed which operates with an annular-blade distributor. Spherical PVC particles (which fall under type D in Geldart's classification) with two different sizes (5.75 and 9.84 mm) were used as bed material to study different bed configurations, taking into account the variation of fraction of open area (12.9 and 17.2%), blade overlapping angles (9° and 12°) and bed weight (500 to 2000 g) for superficial velocities is from 1 to 7 m sec^{-1}. The performance of the swirling fluidized bed was assessed in terms of pressure drop values, minimum fluidization velocity and fluidization quality by physical observation on regimes of operation. The most significant finding is that the pressure drop of the bed increased with superficial velocity after minimum fluidization, in contrast with a conventional fluidized bed. It was also found that the blade geometry has less effect on bed performance, compared to fraction of open area and particle size. New regimes of operation were discovered, and designated as wave regime and two-layer bed regime. The best configuration obtained in the current work, which provides stable swirling at lower pressure drops, is the one with 60 distributor blades and 12° overlapping angle, operating with 9.84 mm particles.

Key words: Swirling fluidized bed, annular distributor, pressure drop, superficial velocity

INTRODUCTION

Fluidization is the operation by which solid particles are transformed into fluidlike state through suspension in a gas or liquid. This method of contacting between solid and fluid has some unusual characteristics, and fluidization engineering puts them to good use (Kunii and Levenspiel, 1991). The basic mechanism of a fluidized bed can be seen simply as fluid percolation through particle interstices via a distributor, in which particles begin to exhibit fluidlike characteristic upon experiencing sufficient drag force from the fluid. A large number of industrial processes use the fluidization technique in their daily operations, namely combustion, gasification of solid fuels, drying of particles, particle heating, oxidation, metal surface treatments and catalytic and thermal cracking (Howard, 1989).

Since half a decade, hundreds of fluidized bed concepts and configurations were patented and came into actual industrial application around the globe. Most of them are specifically designed to serve a particular application as mentioned before. Typically, a fluidized bed is cylindrical in shape and operates using perforated-plate distributor, which holds the particles and distributes the fluidizing gas into the bed. In these types of beds, the fluidizing gas velocity entering the bed can be resolved into three components: axial, radial and tangential components.

The axial and radial components are responsible for the particle movement that causes bed mixing. The tangential component generates mixing along an annular path. The fluidizing gas discharged from the conventional distributor possesses only axial momentum. A deficiency in the radial and tangential momentum leads to vertical mixing many times faster than the lateral mixing (Geldart, 1986). Thus, it had become a classical problem in a fluidized bed to obtain a good lateral mixing and to reduce elutriation of particles during operation.

Innovative techniques have been proposed by various researchers to overcome this issue. One such technique is the swirling fluidization technique or vortexing bed, or sometimes even designated as toroidal bed as proposed by Shu *et al*. (2000) and Wellwood (1997). The swirling fluidization technique minimizes the axial momentum transferred to the particles by the fluidizing gas whereas a larger fraction of momentum is now being transferred radially and tangentially. The particles are now subjected to vigorous mixing which eventually increases the heat and mass transfer, to and from the bed, while reducing the elutriation of particles.

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Typical methods of achieving swirling fluidization are through the secondary injection of fluidizing medium into the freeboard tangentially or by using a distributor which provides inclined injection of the fluidizing medium into the bottom of the bed. Other known methods are simply by either rotating the distributor or the bed column at certain angular speed.

The current study focuses on swirling fluidization using an annular blade distributor. In spite of the potentials for vast industrial applications of the swirling fluidized bed, there are very few systematic studies of such a bed, though the principle has already been used in commercial equipment. From the literature review carried out, there is an apparent lack of reliable experimental data related to the hydrodynamic regimes and characteristics, particularly those operating with large particles. Because of the stable mixing regime with the absence of bubbles and hence, of gas bypassing through slugging, swirl bed has a bright future in solid-gas processing.

Thus the current research was carried out to investigate the regimes of operation and hydrodynamic characteristics of such bed with different configurations, considering two fraction of open area (12.9 and 17.2%), two particles sizes (5.75 and 9.84 mm), variable bed loadings (0.5 to 2 kg) for increasing superficial velocities up to 7 m sec^{-1}. Discussion and explanations were also given accordingly.

Many researchers proposed the swirling fluidization technique as a means to overcome the deficiencies in the conventional beds. Chyang and Lin (2002) proposed a multi-horizontal-nozzle distributor design to improve lateral mixing. The distributor offers the fluidizing gas additional momentum in both radial and tangential directions while minimizing the axial momentum. They conducted pressure fluctuation and fines elutriation experiments using glass beads in cold bed before comparing with conventional fluidized bed (perforated-plate distributor). The authors reported that the multi-horizontal nozzle distributor produced remarkable improvement in fluidizing quality with reduced elutriation of fine particles but the presence of dead zone under and between the nozzles could not be avoided and thus the particles in this region remained defluidized.

De Wilde and Broqueville (2008) experimented a new concept of rotating fluidized. The bed applies the injection of fluidizing gas tangentially in to the fluidization chamber via multiple entry gas inlet slots in its cylindrical wall while rotating at a certain speed. The fluidizing gas is forced to exit from the bed through a centrally positioned chimney. As the tangential entry gas fluidizes the particles tangentially, a swirling field is created while the rotation of the bed creates a centrifugal field. The authors report that sufficiently high solid loading is crucial to obtain a stable and uniform fluidization. The fluidizing gas flow rate was found to have a minor effect on fluidization. The performance of the bed is not addressed, but it is believed to be low. The configuration of the bed is highly complicated, suggesting a high initial and maintenance cost.

Similar study was done by Wormsbecker *et al.* (2007). They investigated the influence of three different types of distributor on a fluidized bed dryer hydrodynamics. The distributors are perforated-plate, wire mesh and punched plate. The punched plate consists of hooded openings of 5.75 by 1 mm oriented in a circular pattern which forms rings, separated by 3 mm from each other. This punched plate distributor was designed to produce a swirling effect in the bed. Fluidization quality was assessed in terms of drying times and standard deviation and power spectrum analysis of the pressure fluctuations. Again, the swirling motion of particles in punched plate distributor is reported to have superior fluidization performance, but at the expense of high pressure drop, and thus not suitable for low cost operations.

Lin *et al.* (1998) reported their findings from numerical and experimental study on the swirling flow field in a Vortexing Fluidized Bed Combustor (VFBC). The VFBC was made by a conventional fluidized bed with four secondary air injection nozzles with tangential entry. The performance of the flow field was assessed based on the vortex number. The results show that the vortex number increased with secondary air injection that creates swirling. However the method is only useful for relatively large beds since the jets from the nozzles tend to interfere with each other for smaller beds, thus weakening the swirl effect. The authors also reported that flow turbulence and elutriation rate could not be established accurately.

Another bed that operates using swirling fluidization technique is the Swirling Fluidized Bed (SFB), which is the main focus in this study. The bed is annular type, featuring angular injection of gas and swirling motion of bed material in a circular path as shown in Fig 1.

The principle of operation is based on the simple fact that a horizontal component of gas velocity in the bed creates horizontal motion of the bed particles. A jet of gas enters the bed at an angle θ_b to the horizontal. Due to angular injection, the gas velocity has two components. The vertical component $U_v = U \sin \theta_b$, causes lifting of the particles. It is this lifting force that is responsible for fluidization. The horizontal component $U_h = U \cos \theta_b$, creates a swirling motion of the particles (Shu *et al.*, 2000; Sreenivasan and Raghavan, 2002). The bed particles are also likely to undergo a secondary motion in a toroid-like path and be well mixed in the radial plane.

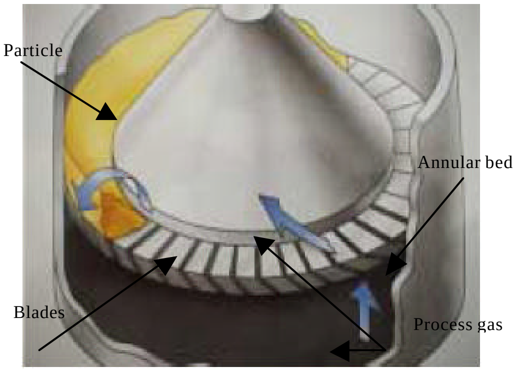

Fig. 1: Basic configuration of a swirling fluidized

This variant of fluidized bed provides an efficient means of contacting between gas and particles. Elutriation of particles which has been a major limiting factor in the operation of the conventional fluidized bed is reduced significantly, since the vertical component of velocity is now only a small fraction of the net gas velocity. The cyclone-like features resulting from the swirling motion of bed particles also contribute to this low elutriation. Hence it is possible to fluidize very fine particles and a wide variety of shapes of particles in this kind of fluidized bed.

Shu *et al.* (2000) studied a similar bed, termed as the toroidal bed, which is taken from the overall shape of the bed in the swirling regime. Relevant hydrodynamic behaviors of the bed are measured with various inert materials in a pilot scale 400-mm toroidal fluidized bed reactor. The observed hydrodynamic behavior is found to be essentially predictable at ambient temperature by conventional hydrodynamic models.

Earlier Wellwood (1997) described the toroidal gas–solid action as ‘horizontal fast fluidization’ and attempted to predict the slip velocity in dilute gas–solid systems by using an equation analogous to the ideal gas equation. The study was based on the observed similarities between microscopic molecules and macroscopic particles. Thus, the author adopted an assumption that under dilute phase conditions, the analogy is applicable. He concluded that the experimental results gave general support for the analogy approach.

Sreenivasan and Raghavan (2002) developed an analytical model on the hydrodynamics of a swirling fluidized bed. The model is put forward to predict the angular velocity of the swirling bed at given air flow rate and also the pressure drop of the swirling fluidized bed. In this model, the bed is treated as a lumped system; the whole bed is a single swirling mass of uniform angular velocity. The model was developed based on the conservation of angular momentum principle and the authors validated the model with experimental works.

Recently, Kaewklum and Kuprianov (2010) investigated the hydrodynamic regimes and characteristics of a conical fluidized bed operating with annular-blade distributor. Using quartz sand with four different particle sizes, they compared the pressure drop and minimum fluidization velocity with four-nozzle tangential entry system which also generates swirling motion in the bed. From the cold model tests, they concluded that the method of air injection substantially affected the hydrodynamics and fluidization regimes. However, the swirling effect can only achieved at higher superficial velocities, particularly with low bed heights.

Using the same bed with annular-blade distributor, (Kaewklum *et al.*, 2009) again reported hydrodynamics, now together with combustion and emission characteristics of rice husks. Four regimes of operation were obtained, favoring the fully swirling regime where the combustion temperature profiles were rather uniform, suggesting intense heat and mass transfer in the radial direction. The authors concluded that the swirling fluidization in the conical bed yielded very high combustion efficiencies coupled with reduced emissions.

Though comprising such merits, the SFB also comes with several drawbacks. Towards attending to these deficiencies through the proposal of a novel distributor, it is imperative to first understand fully the existing bed characteristics and other bed configurations which have not been addressed in the literature.

MATERIALS AND METHODS

A well-planned methodology is important to meet the desired project objectives. Here, details of the experimental apparatus including distributor design, blower selection, flow measurement and experimental procedure for pressure drop measurement are discussed.

Annular distributor: The distributor assembly consists of lower and upper flanges together with inner plates respectively, holding the blades firmly to form the annular distributor, somewhat similar to that used by Shu *et al.* (2000), Sreenivasan and Raghavan (2002), Kaewklum and Kuprianov (2010) and Kaewklum *et al.* (2009). The centre body is important to avoid the possible creation of ‘dead zone’ at the centre of the bed during operation with bed materials. Air enters the plenum chamber via tangential entry and expands before entering the annular blade distributor.

Particle and blades description: Particles used in this experiment are large spherical PVC beads, which fall in

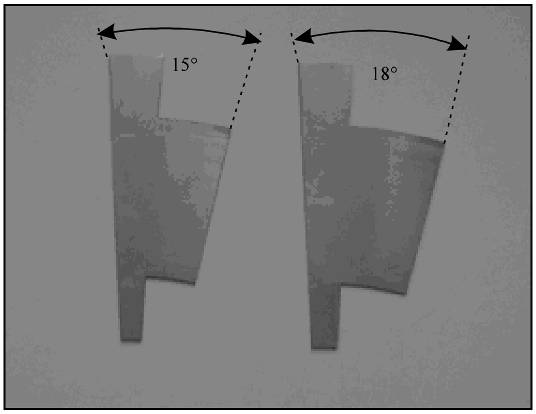

Fig. 2: Blades used to form annular

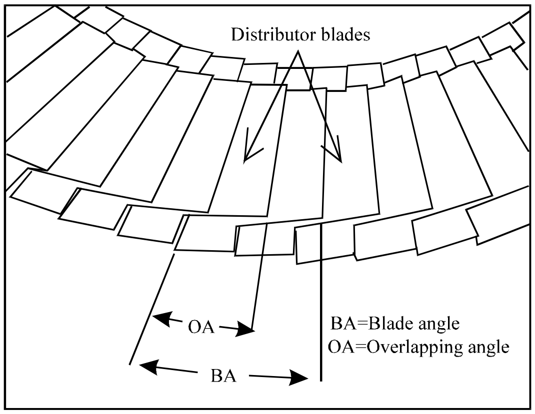

Fig. 3: Blade angle and blade overlapping angle

Table 1: Particle density and size

Parameter	Density (kg m^{-3})	Diameter (mm)
Particle 1	950	5.75
Particle 2	840	9.84

Geldart type D particles as proposed by Geldart (1986). Two different sizes of particles are used, with their respective density and diameters are shown in Table 1.

Similarly, two versions of blades with different geometry are used in the current work as shown in Fig. 2. The blades resemble the shape of truncated sectors of a circle, having angles of 15° and 18°, respectively.

The overlapping length between two successive blades helps to direct the air at the designed angle. Larger overlapping lengths of blades may result in higher distributor pressure drop. This is because larger overlapping lengths constrain the flow of air much longer between the blade s before it enters the bed. Since the blades resemble the shape of sectors as shown above, the over-lapping length is more appropriate to be termed as blade overlapping angle as shown in Fig. 3. Larger angular value naturally represents larger over-lapping area of blade. Thus, the 15° and 18° blades have the overlapping angles of 9° and 12°, respectively.

RESULTS AND DISCUSSION

The findings from hydrodynamic characteristics for various bed configurations are presented and the regimes of operation observed are also discussed.

- Variation of bed loading (0.5 to 2 kg)
- Variation of particle sizes (9.84 and 5.75 mm)
- Variation of FOA (12.9 and 17.2%)
- Variation distributor of blade overlapping angle (9° and 12°)

Findings from this study were also compared with those of a conventional fluidized bed with perforated plates which has the same fraction of open area and bed loading.

Regimes of operation: Typical regimes of operation in a conventional fluidized bed include packed bed, minimum fluidization, bubbling, slugging and finally elutriation. While operating a SFB, one can distinguish different regimes of operation as shown in Fig. 4. Though the packed regime (Regime I) still exists, progressive increase of fluidizing gas flow rate upon minimum fluidization led to a condition suitably designated as the minimum swirling condition (Regime II) where the bed almost swirls. Few particles even started swirling gently at this point. Further increase in fluidizing gas flow rate results in the desired swirling motion of the bed (Regime III). At this condition, the bed is subjected to both fluidization and swirling where vigorous mixing occurs and interaction between gas and particles are intense. This regime was the largest regime where the particles tend to swirl faster with the increase of fluidizing gas (thus increasing pressure drop) until finally reaching elutriation (Regime IV) for shallow beds (bed weight less than 1000 g).

For deeper beds, 1500 g bed loading for instance, a two-layer bed is observed as reported by Sreenivasan and Raghavan, (2002), Chyang and Lin, (2002), Kaewklum and Kuprianov, 2010). In a two-layer bed which occurs at a static bed height greater than 45 mm, a thin, continuously swirling bottom layer and a vigorously bubbling top layer are visible upon minimum swirling velocity. This is because the horizontal component of the velocity is attenuated and finally vanishes at the interface between the two layers as a result of continuous momentum transfer inside the bed. This regime is shown in Fig. 5.

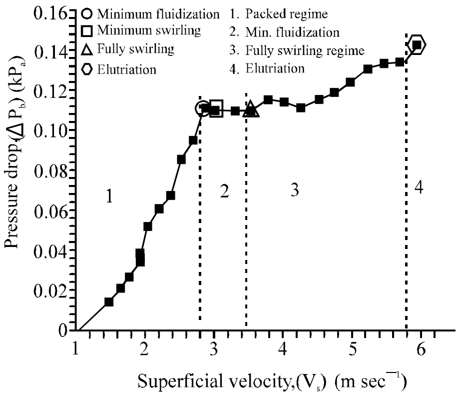

Fig. 4: Regimes of operation in the SFB for shallow bed (1000 g bed loading)

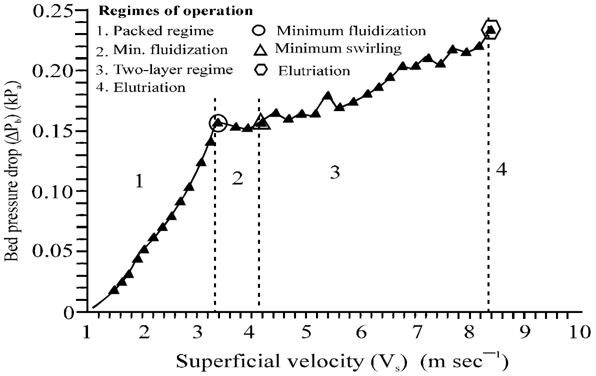

Fig. 5: Regimes of operation in the SFB for deep bed (1500 gram bed loading)

Effect of various bed configurations: Various configurations of the swirling fluidized bed as outlined in the previous section are studied through batch experiments and presented in the following section. Apart from pressure drop and minimum fluidization velocity, quality of fluidization is determined qualitatively through observation.

Effect of variable of bed loading: Bed loadings were increased from 500 to 2000 g in steps of 500 g to investigate the effect of variable bed loading, which also corresponds to its respective bed height. Figure 6 shows ΔP_b against V_s with cone as centre body. As mentioned earlier, ΔP_b increased with the increase of V_s upon minimum fluidization. This distinct feature differentiates the SFB from conventional beds. The reason for this feature is the increase of centrifugal bed weight, which results in higher wall friction as proposed by Sreenivasan and Raghavan (2002), apart from increasing friction between particles. For deep beds, i.e., higher bed loadings, a two layer bed appeared, a swirling bottom layer and bubbling top layer as discussed earlier. Higher bed loading naturally impose higher pressure drops. With cylinder as centre body, slightly higher pressure drops were obtained for all bed loadings.

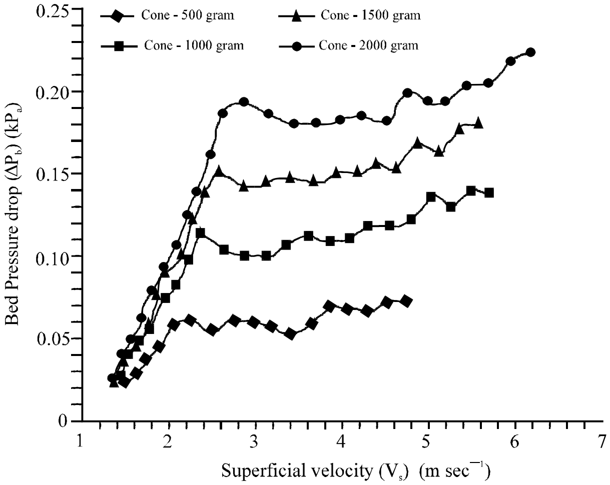

Fig. 6: Bed pressure drop against superficial velocity for variable bed loading

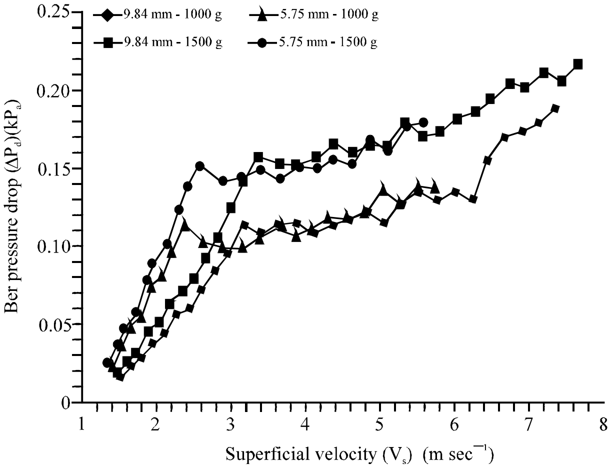

Fig. 7: Bed pressure drop against superficial velocity for different bed weight

Effect of particle size: Batch experiments were conducted with two different particles, 5.75 and 9.84 mm for two different bed weights as in Fig. 7.

It can be seen that in the packed region, larger particles have lower pressure drop for both bed weights. This is due to the fact that smaller particles actually have a larger surface area. Larger particles, on the other hand, are capable of withstanding higher superficial velocity and hence longer swirling. Similar trends are found for 1500 g bed weight for both particle sizes.

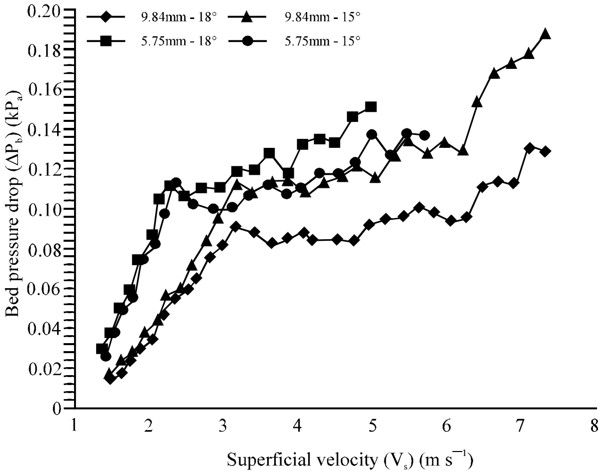

Fig. 8: Bed pressure drop against superficial velocity for different blade overlapping angle

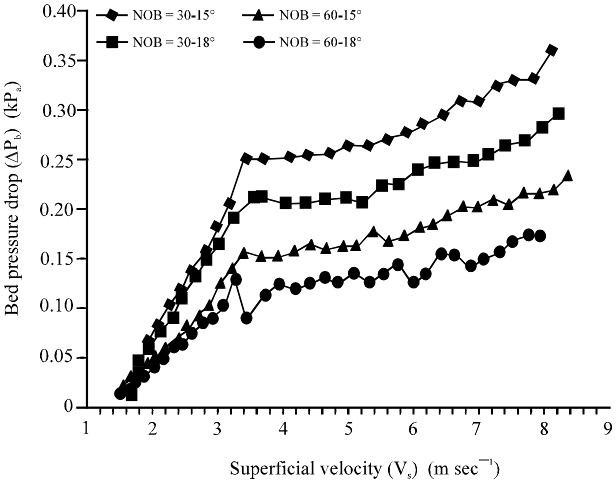

Fig. 9: Bed pressure drop against superficial velocity for different number of blades

Effect of distributor blade overlapping angle and number of blades: To bring out the effect of blade overlapping angle, two sets of distributor blades, having 9° and 12° overlapping angles were investigated. Though higher overlapping angle was expected to impose higher pressure drop since air is forced to flow through longer blade opening, thus higher resistance, the findings yield that this is not true to all bed configuration. Figure 8 show that higher overlapping angle results higher pressure drop only for 5.75 mm particles, while experiments with 9.84 mm particles suggest otherwise. Less pressure drop consumed with larger overlapping length of blade, which is actually good in terms of energy saving during operation.

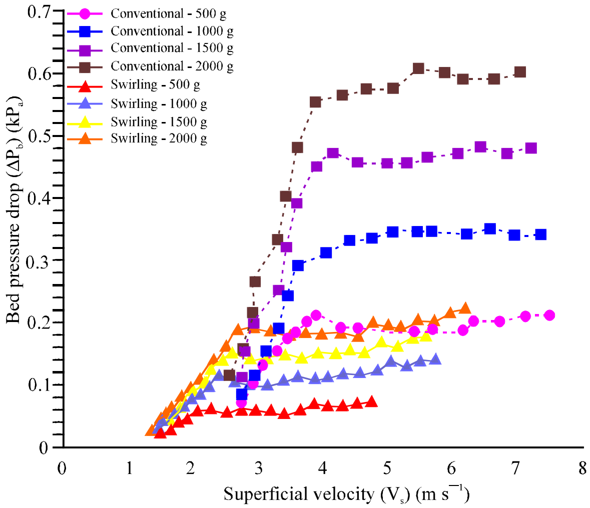

Fig. 10: Bed pressure drop against superficial velocity with cone as centre body

In Fig. 9, the number of blades is varied to observe the effect fraction of open area (FOA). The FOA for 60 blades is calculated to be 12.89% from total distributor area, while for 30 blades, the FOA is 17.2%.

By using smaller number of blades, which is 30 blades in our case, the distributor has larger FOA compared to that of 60 blades. Thus, larger momentum is now transferred to the bed, resulting in higher pressure drop values in bed as depicted in the Fig. 9 above. Operating with smaller particles also exhibits similar feature where the bed pressure drop is higher for beds with smaller number of blades (higher FOA).

Comparison between conventional fluidized bed and SFB: Bed pressure drop against superficial velocity for both conventional fluidized bed and SFB is also made, having the same fraction of open area, as in Fig. 10.

Figure 10 clearly shows that SFB requires only half of the potential energy for fluidization compared to the conventional bed. This is true for all SFB configurations, including both small and large particle size. Apart from that, the minimum fluidization velocities are also lower for SFB. Therefore, it leads to a conclusion whereby SFB is superior compared to the conventional fluidized bed. Therefore, we can expect better output when dealing with actual processes involving solid-fluid contact when operating with SFB. However, more experiments are needed to support this finding.

CONCLUSIONS

In conclusion, the SFB has been investigated through batch operations. The findings indicate that the sequence of flow regimes in swirling fluidized bed are packed bed, minimum fluidization, swirling regime, two-layer regime and finally elutriation or transport regime. Deep beds are prone to form partially fluidized regime and two-layer beds. Various configurations were also investigated and the study concludes as below:

- The hydrodynamics of swirling fluidized bed are different from other conventional fluidized bed, in which the pressure drop increases with the mass flow rate of fluidizing gas
- Larger particles have lower pressure drop and capable of withstanding higher superficial velocity and hence, larger swirling regime
- Larger overlapping angle imposes additional pressure drop, particularly at the distributor since the air is now forced to flow through higher resistance. But, larger overlapping angle also delays the presence of two-layer as well as reducing the elutriation by expanding the swirling region
- Particle size, bed weight and the number of blades (FOA) are the most important variables that have more influence on the bed behavior. The blade geometry has relatively smaller effect on the bed behavior.

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