Effect of Particle Density on Particle Motion of a Swirling Fluidized Bed with Mesh-type Distributor

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Abstract: Swirling Fluidized Bed (SFB) have several variant of distributor and the well known is annular distributor. But, there is no available research investigates about SFB with Mesh-type distributor. Investigate a new variant of distributor is needed, since distributor is main actor responsible to distribute gas into bed column and high pressure drop is major drawback of current distributor design in SFB. Particle image velocimetry was used to elaborate the behavior of particles fluidized with increasing superificial air velocity. The particle motion within a swirling operation of a SFB with-Mesh type distributor is investigated. The main objective of this research is to investigate the effect of particle density in swirling fluidized bed with mesh-type distributor on the particle motion by analyzing the velocity field of the bed particles. The effects of bed weight and particle size on the fluidized particle velocity were also investigated. The effect of particle density will only exhibit significant effect to particles motion when it compared with particles that have similar size. Particle density influence to the superficial velocity needed to get the particle fluidized. Particle that has less density required less superficial velocity than the other particle that has more density. Although the bed weight increased, the trend of particles velocity still exponentially increased. Particle sizes with different bed weights coincide with each other and deviate with other sizes of particles. It emphasizes that usage of different sizes of particle may have a significant influence on the particle velocity as compared to the bed weight.

Key words: Swirling fluidized bed, mesh-type distributor, particle image velocimetry

1. Introduction

Fluidized bed is an advance technology, which possesses a number of characteristics ideal for a wide variety of industrial applications. It is a technology that uses the technique of suspending solids through gas, and gives the solid a fluid-like behavior. Due to its high efficiency and flexibility, fluidized bed is widely used in many chemical and mechanical processes. Since, the first development of fluidized bed, some of conventional beds have been developed including centrifugal fluidized bed, vibro-fluidized bed, tapered fluidized bed, spouted fluidized bed, etc. (Howard, 1989).

Fluidized beds provide a lot of advantages, such as good particle mixing, uniform thermal distribution, good adaptability to high-pressure and temperature operations, continuous particle addition or removal and easy transport of particles.For decades, fluidized beds of different geometries have been used in various applications, such as combustion, drying, gasification of biomass fuels, metal surface treatment, thermal and catalytic cracking, coating, etc. (Naz and Sulaiman, 2016).

Despite the advantages provided by fluidized beds, conventional fluidized beds have several shortcomings that affects the quality of fluidization in relation to moving parts, particle mixing, pressure drop, hydrodynamics, and

limitation in using variety particle sizes. Swirling Fluidized Bed (SFB) is a recent technology on fluidized bed that has been developed by researchers to overcome the shortcomings of conventional fluidized bed. SFB provide superior features that are able to provide better quality of fluidization, such as, no moving parts in SFB, excellent particle mixing resulted uniform motion of particles, reduces elutriation, lower pressure drop, and allows application of variety particle sizes (Amonsirirat et al., 2011).

SFB has several variants of bed distributor; the most popular one is SFB with annular distributor. The concept of annular distributor was inspired from spiral distributors, which proposed by Ouyang and Levenspiel (1986) and improved by Shu et al. (2000). Another variants of distributor were introduced by Paulose (2006), which are; (i) single row vane distributor, (ii) inclined hole type distributor, (iii) three row vane type distributor. Aworinde et al. (2015) introduced a helical nozzle distributor to induce swirling air motion as the air enters the fluidized bed. The review of available works shows that the type of distributor design significantly affects the operation of the fluidized bed. However, high-pressure drop across the distributor become the most concern since it is one of major drawbacks of the current distributor designs (Shukrie et al., 2016).

In fluidized bed technology, bed pressure drop is a crucial factor as it determines the pumping power required to distribute the gas to bed. Different than conventional fluidized bed, in SFB the bed pressure drop in swirl mode increases with air velocity, because the bed pressure is proportional to centrifugal weight of the bed (Sreenivasan and Raghavan, 2002).

Therefore, a new variant of distributor in SFB operation has been discovered as an effort to bring forth a better operation of SFB. Even though SFB has been implicated, it has not been fully developed and is resulted in development of new concepts of the distributors. Mesh-type distributor is the latest among them. There is scant published information on the operation of SFB with mesh-type distributor. Thus, an experiment is required to study the particle behavior to have a better understanding of the particle velocity and motion on this variant of SFB.

The main objective of this research is to investigate the effect of particle density in swirling fluidized bed with mesh-type distributor on the particle motion by analyzing the velocity field of the bed particles. The effects of bed weight and particle size on the fluidized particle velocity were also investigated. In order to accomplish, a velocity measuring technique is conducted by using Particle Imaging Velocimetry (PIV), processed with a High-speed camera and analysis tool in MATLAB for post processing.

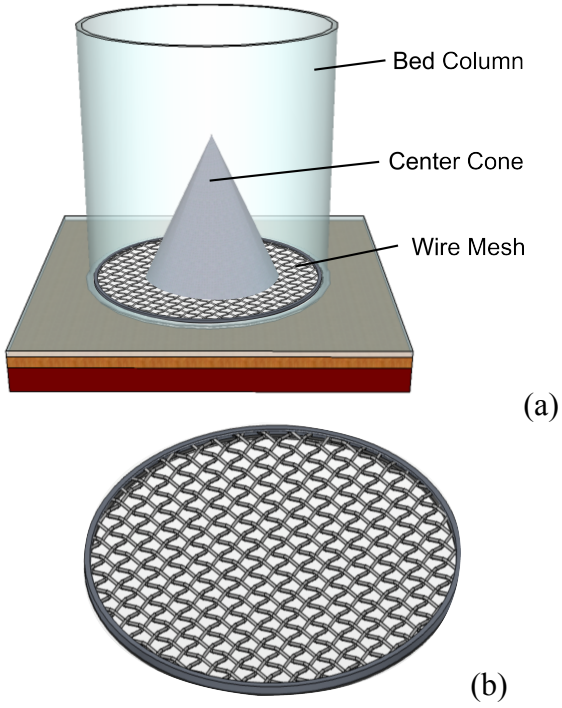


Fig 1. (a) Mesh-type distributor with center cone, (b) Wire mesh

2. Experimental Study

The experiments were carried out on a laboratory scaled SFB with mesh-type distributor and parameters including particles size, bed weight and particle density were determined. Particle Imaging Velocimetry was utilized to obtain velocity field.

A. Experimental Set-up

Figure 2 illustrate a laboratory scale swirling fluidized bed with a mesh-type distributor was set up. A wire mesh was arranged on inside bed column with a 10 cm hollow metal cone placed in the center of the bed. A 20 cm diameter of Plexiglass bed column was fixed on the bed with bolts and nuts. A 5.5 kW high-pressure blower with a maximum static pressure of 600 mm w.g. and flow rate of 1000 m^3/hr was connected to the wind box at the bottom of the fluidized bed through a 10 cm diameter pipe with an orifice plate located in the middle of the pipeline to measure the pressure of the air flow. The pressure recorded was used to calculate the superficial velocity of the air entering the distributor.

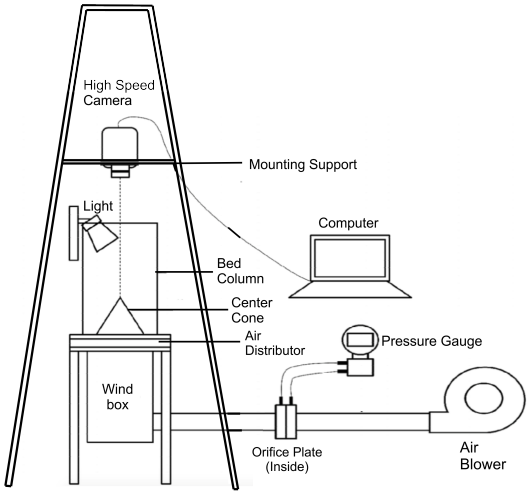


Fig 2. Schematic of a laboratory scale SFB with a mesh-type distributor

B. Imaging Study on the Motion of Particles

PIV is selected as the measuring method due to its less complicated algorithm and it is remarkably noise-tolerant and robust in comparison to PTV. The fluid flow is visualized by seeded particles or dye materials and their motion in the whole flow field can be measured from a series of consecutive images in order to recognize its trajectory and to derive the velocity vector field. To distinguish the tracer particles from the flowing particles, a mixture of black and white as well as blue and white particles were used rather than particles of just one colour. The white particles gave good light reflection to the camera, which enabled them to be the tracer particles in this experiment.

Generally, PIV uses laser sheeting perpendicular to the imaging direction or a fluorescent illumination behind the measured area for the illumination purpose. However, in this experiment both of these lighting methods could not be applied since this system was opaque and observations were limited to the top layers of the bed. Thus, only images of half of the bed were taken, by photographed half of the bed also could lead to increase the accuracy of experiment result.

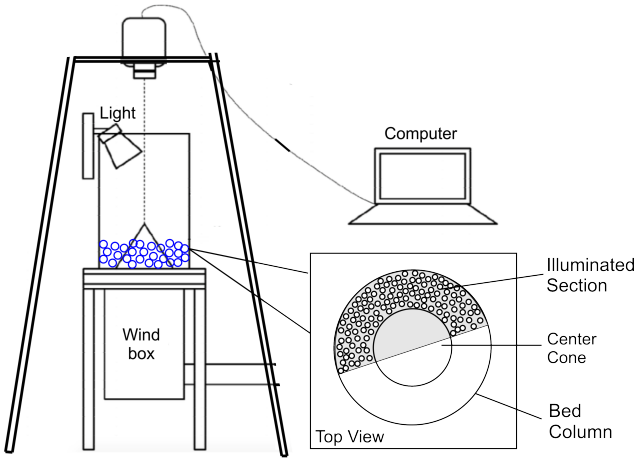


Fig 3. Illumination system for swirling fluidized bed

Photographed half of the bed also can help to understand more about regime that occurred when the particles experience turbulent. However, The circular motion of the particles

was assumed to be the same no matter which half section was chosen because it was a circle.

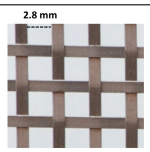
The camera lens was adjusted until a clear image was obtained. Suitable resolution was set and in this case was 864 x 856 pixels then a static image of the whole bed without any movement of the flow was taken. The known dimensions such as the diameter of the bed column and the diameter of the center cone in the image were used to give the real scale or coordinate for the calculation of displacement and velocity in image processing. Exposure time (430 μs to 990 μs) and frame rate (1200 pps to 2200 pps) were adjusted in order to match with the illumination condition and the particle velocity.

In this experiment, Binary Image Cross-Correlation Method (BICC) was used for the measurement of displacement and velocity. According to Abdulmouti and Mansour (2006), this method employed an algorithm of particle distribution pattern tracking. The motion of each tracer particle was tracked based on the highest similarity of particle distribution patterns in two-consecutive images. The pattern was used for pattern matching and which will give information about the displacement. Then the displacement could be divided by the time interval (from frame rate) and the velocity was obtained. In order to execute image processing, Matlab software was used. First, "world-coordinates" had to be defined.

The "unwanted" area with no velocity was masked out so that no calculation would be done on that region. With that, calculation of velocity was started. To calculate the velocity of the tracer particles, the image was subdivided into smaller regions called interrogation-windows. The interrogation windows could be of 64 x 64 pixels, 32 x 32 pixels or 16 x 16 pixels. In this experiment, 32 x 32 pixels of interrogation window were used to suit the number of particles. The particles pattern in a sub- window in the first image with the corresponding sub-window in the second image was compared and this comparison continues to the following interrogation windows till it ended. Thus, in the next step, filtering was to be done. There are basically three filters used, which were signal-to-noise ratio filter, global filter and local filter. Since filters had eliminated some vectors, there were holes left in the velocity field. Then, an Interpolation from neighboring velocities is needed to obtain a complete velocity field.

To investigate the particle motion of the particles, several parameters are chosen to study their effects on the particle velocity. The parameters include wire mesh, particle size, particle density, superficial velocity (air velocity) and bed weight.

Table 1. Description of bed parameters

Parameter	Description
Wire mesh	
Particle size	 D = 3mm Mass = 0.025 g; D = 4mm Mass = 0.1 g; D = 6mm Mass = 0.25 g
Particle Density	 D = 3mm Density = 1.77 g/cm3; D = 4mm Density = 2.99 g/cm3; D = 6mm Density = 2.21 g/cm3; D = 6mm Density = 2.65 g/cm3
Superficial Velocity	Velocity ranges in steady state swirling regime of operation and early bubling regime of operation
Bed Weight	500, 750, 1000, 1250

Wire mesh with 2.8mm^2 size is used in this experiment. Three different sizes of sphere PVC particle (6mm, 4mm, and 3mm) were selected for the investigation of the effect of particle size. Four different density of sphere PVC particle (1.77 g/cm^3, 2.99 g/cm^3, 2.21 g/cm^3 and 2.65 g/cm^3) were selected for the investigation of the effect of particle density. Superficial velocity of the air entering the bed was adjusted within the range of producing stable swirling regime of operation and the bed weight varied from 500 g to 1250 g with increment of 250 g, were used.

3. Results and Discussions

Velocity fields were generated from the PIV program and five particle velocities were averaged to obtain final velocities. Figure 4.3 illustrates one of the velocity vector fields gained for the 750 g bed weight of 6mm diameter sphere particles with 2.21 g/cm^3 particle density at 103 mm H_2O pressure drop and 2.2828 m/s of superficial air velocity. Figure 4.4 illustrates the velocity streamlines field that shows the flow path of the majority of particles moving around the bed. The velocity field shows the particle trajectory and the color bar indicates the velocity in m/s unit.

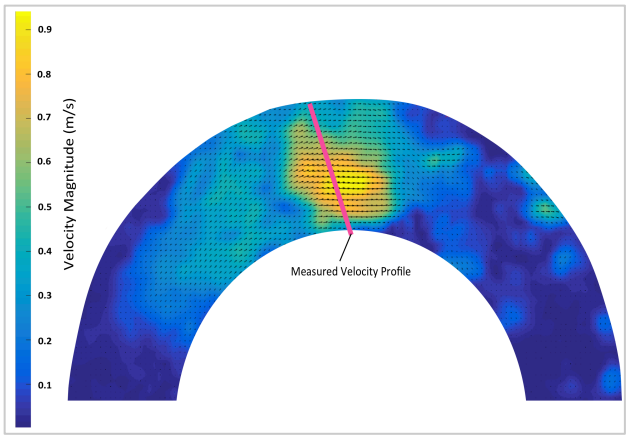


Fig 4. Typical velocity vector fields of particles

From the velocity field, it could observed that particles is not moving in uniformity, it shows particles in some area do not have velocity. It is due that at this time the particles are experienced minimum superficial velocity. The area with yellow color shows particles with highest velocity where the particles were about to turn at the corner. This area was selected to be measure in order to know the maximum number of U velocity in particular superficial air velocity. Figure 5. shows the graph of U velocity of particles in the measured area, the maximum velocity is obtained from the velocity magnitude data that represent the area and average velocity was calculated from the overall velocity of velocity magnitude data.

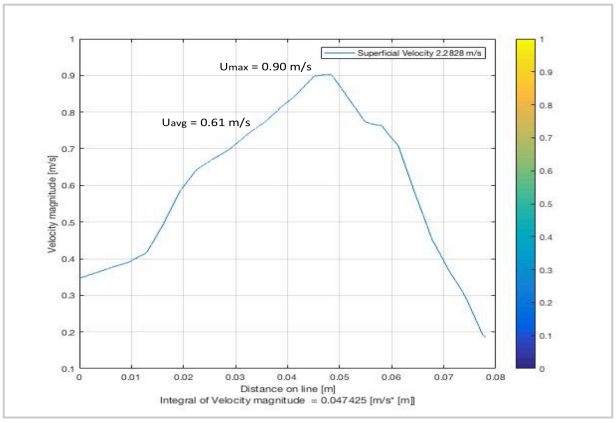


Fig 5. Graph of U-velocity of particles in the measured area

Different pattern of velocity could be obtained depending on which area is selected to be measure regardless of the superficial air velocity. The U-velocity of particles is generated for each particle with 500g of bed weight with increasing air superficial velocity. 500g-bed weight is selected to generate the U-velocity of each particles due it sensitivity to superficial air velocity and demonstrate the velocity profile of particles with increasing superficial air velocity.

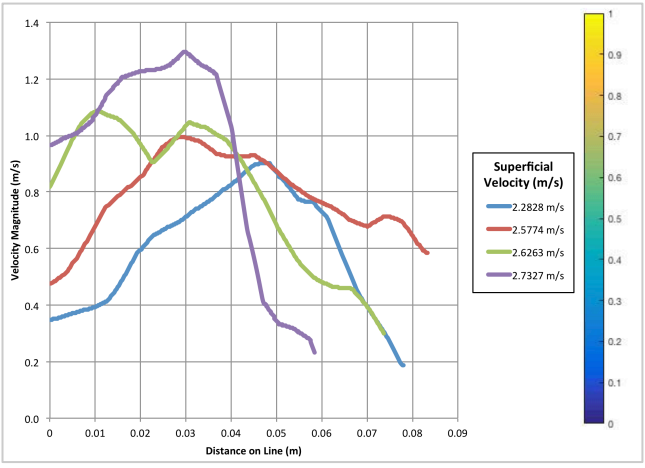


Fig 6. Graph of U-velocity in the measured area with increasing superficial air velocity

The graphs are obtained from the velocity field in each superficial air velocity. Each graph represent different measured area with one and another,

since the velocity fields of each superficial velocity has different area where particles reach the maximum number of U-velocity. However, it can be observed that maximum U-velocity is increase as the superficial velocity increased.

At low superficial velocity, the particles are moving very slow because it experienced minimum superficial air velocity. Moreover, particles near bed column wall and center cone were slowed down by friction. Particles, which contacted with center cone surface possessed lowest velocity while particles in the middle region had highest velocity. As superficial velocity increased, the velocity near surfaces started to increase as the swirling momentum of particles was sufficient to overcome the friction. The velocity of particles which was in contact with bed column wall, remained at low value regardless of increasing superficial velocity. This was due to the centrifugal force, which had increased with superficial velocity. Strong centrifugal force pushed the particles towards bed column wall, which increased the inter- particle friction and surface friction. However, this centrifugal force had reduced friction on the inner radius particles, which enabled the particles to swirl at highest velocity.

Table 2. Velocity profile with increasing superficial air velocity

Superficial Velocity (m/s)	Umax (m/s)	Uavg (m/s)
2.2828 m/s	0.90	0.61
2.5774 m/s	1.00	0.79
2.6263 m/s	1.09	0.81
2.7327 m/s	1.30	0.94

A. Effect of the Particle Sizes

Figure 7. shows the velocity variation of 6mm, 4mm, and 3mm spherical particles, with air superficial velocity at bed weights of 500 g and 750 g. For this variable, only two bed weights were available for comparison, this was mainly due to the small particle 4mm and 3mm spherical particles which had no stable swirling regime of operation but dynamic regime with two layers of regime were formed where small area of particles are swirling at the bottom of the bed and larger area of particles vigorously bubbling on the top when the bed weight exceeded 750 g.

From the graph in Figure 7., it observed that generally the particle velocity of three sizes of particles increased with superficial air velocity. It was found that 3mm spherical particles had lowest minimum swirling air superficial velocity than 4mm and 6mm spherical particles. For 500 g bed weight, the 3mm spherical particles started to swirl when superficial air velocity was approximately 1.4 m/s while 4mm and 6mm spherical particles reached stable swirling at 1.5 m/s and 2.2 m/s respectively.

This implied that stable swirling regime of operation in the smaller particle also ended earlier and thus the operating regime of superficial velocity was shifted down. The graph in Figure 7. shows that the maximum superficial air velocity for stable swirling regime is lower for smaller particles. 3mm and 4mm sphere particles reached maximum superficial air velocity at 1.6 m/s and 2 m/s respectively and on the other side 6mm sphere particle reached maximum at 2.4 m/s. For 750 g bed weights a similar trend is indicated, the minimum and maximum point of air superficial velocity of three particle sizes are lower for smaller particles. But, on the other side, generally observed that the particles velocity of three particles is less than compare to particles with 500 g bed weight. It also found that particles with 750 g bed weights need slightly more superficial air velocity to get the bed fluidized. This is due to more weight of bed therefore more airflow is needed.

In the research did by Sulaiman et al. (2016) who studied about the effect of particle sizes in SFB with annular distributor found that graphs for any particles of the same bed weights coincide with each other. In the present study, SFB with

mesh-type distributor exhibit contrary result. From the graph in Figure 7., it found that particle size with different bed weights coincide with each other and deviate with other sizes of particles. This finding can be suggests that, apart from the minimum and maximum particle velocities, the interparticle space caused by usage of different sizes of particle may have a significant influence on the particle velocity as compared to the bed weight.

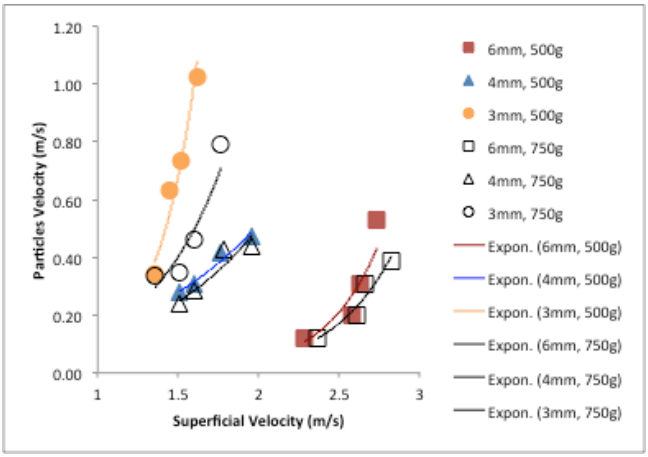


Fig 7. Variation of particle velocity for different spherical particle sizes

B. Effect of the Bed Weight

Figure 8. shows the variation of 4mm sphere particle velocity with superficial air velocity at different bed weight, which varied from 500 g to 1250 g at an increment of 250 g. Generally it observed that particle velocity decreased with the bed weight. This was due to the associated increase in bed height due to the more bed weight of particles. It was observed that, as the bed become weightier and the jet of air percolated through the bed, it velocity continuously decreased due to the transfer of momentum to the particles. Consequently, the particle in the uppermost layer decayed as the bed height increased.

From the graph of Figure 8 it can be found that changes in bed weight did not influence the minimum superficial air velocity needed to get the particles fluidized initially, however it affected the minimum point of particles velocity with bed weight. It is contrary with the findings of Sulaiman et al. (2016) in the experiment of SFB with annular distributor. In SFB with annular distributor minimum superficial air velocity increased with bed weight to get the particles fluidized. It can be conclude that in annular distributor when processing particle with more bed weight it will need more pressure drop to distribute air to the bed, hence more energy will be needed. This finding can be suggests that, when processing particle with more bed weight, SFB with mesh-type distributor is more superior because it need less energy to get the particles fluidized.

When the bed weight increased, the particle velocity was less sensitive to superficial air velocity. Correspondingly, particle velocities become less sensitive to the changes of superficial air velocity with bed weight. This can be observed from the graph that the range of particle velocity of 500 g bed weight is larger than other particles with more bed weight and the particles velocity decreased as the bed weight increased. In this case, heavier bed weight have large amount of particles, which resulted in higher friction between the particles as well as wall friction.

Another finding from graph of this experiment is that, interestingly even though the bed weight increased, the particles velocity of heavier bed weight still exponentially increased. In the experiment of Sulaiman et al. (2016) in SFB with annular distributor indicates that, in bed weights above 750 g the particles velocity remained almost constant regardless of an increase in the bed weight. This finding can be suggests that, when it comes to processing particles with more bed weight, SFB with mesh-type distributor is more superior because, although the bed weight increased, the trend of particles velocity still exponentially increased, hence particles can be processed better in SFB with mesh-type distributor.

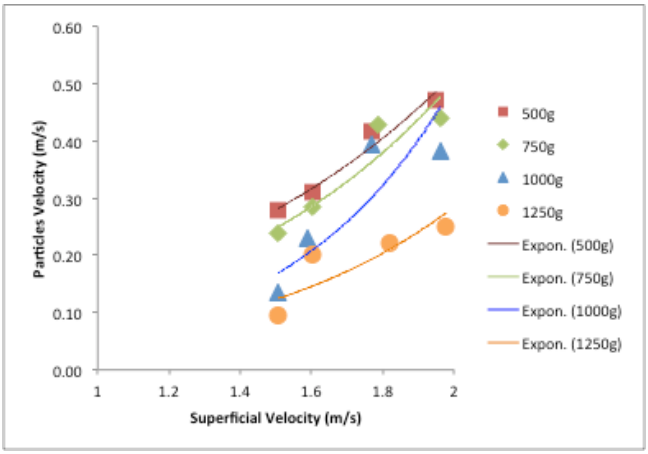


Fig 8. Variation of particle velocity for different spherical bed weight

C. Effect of the Particle Density

Generally observed that overall particles velocity of different particle densities are decrease as the bed weight increase. However, the effect of particle density will only exhibit significant effect to particles motion when it compared with particles that have similar size. Due to the limitation of available particles, for this analysis it only uses both 6mm diameter particles with different particle density.

It is found that, particle density influence to the superficial velocity needed to get the particle fluidized. Particle that has less density required less superficial velocity than the other particle that has more density. Then, it can be proposed that when processing particles with different density can cause to significant influence to particles velocity in fluidized bed, since particles with different density occurred differently to the superficial velocity. However, contrary result is exhibited for particles that have different particle size and density.

Contrary result is occurred when it compared with particles that have different sizes with different density. Even though 4mm particle have more density than 6mm particle, the superficial velocity needed to get the particle fluidize is less than 6mm particle. Furthermore, the particles velocity is exponentially higher than 6mm particle. It is because the heavier particles that experience stronger gravitational force due the more weight of particle that influence more superficial air velocity required to get the particle fluidized and cancel the effect of density in fluidization of the particles (Naz et al, 2016). As mentioned by Groot et al. (2002), the significant factors that affecting the fluidization are the bed material type and weight per unit cross-sectional area of the bed. Thus, it can be suggests that the effect of density will not occurred when processing multi-sizes particles in a SFB with-mesh type distributor.

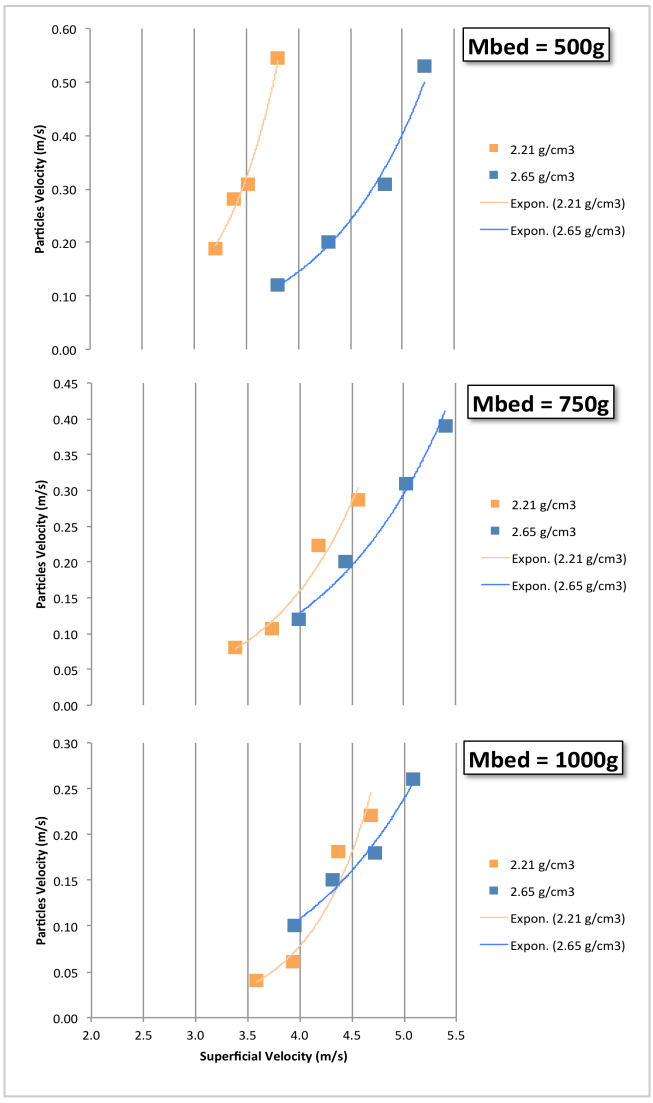


Fig 9. Variation of particle velocity for 6mm diameter particles with different particle density

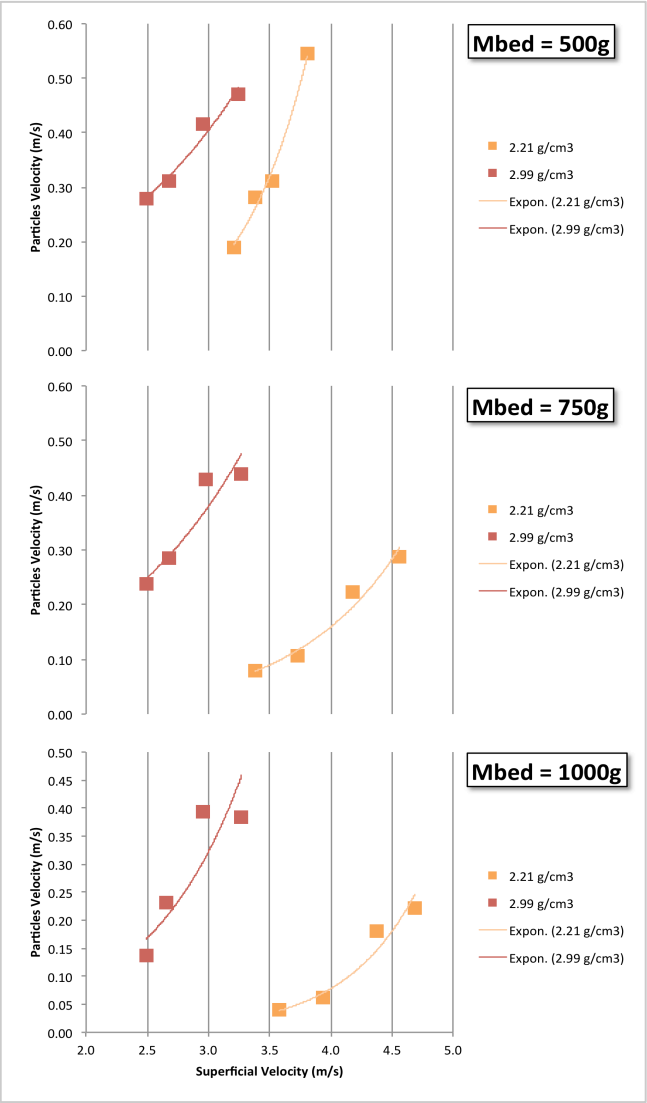


Fig 10. Variation of particle velocity for 6mm and 4mm diameter particles with different particle density

4. Conclusions

From the analysis, which has been done, following conclusions were obtained:

1) The decrease of particle velocity in response to increasing bed weight and reduction of superficial velocity were in conformity with theories. An interesting finding was that when bed weight was increased, the particle velocity was less sensitive to the increase of superficial velocity.
2) It proposed that smaller particle size would be preferred for applications of shallow bed with the reason that lower air superficial velocity is sufficient to start swirling the particles as compared to bigger particles, implying that less energy would be needed to swirl small particles.
3) In the present study, SFB with mesh-type distributor exhibit contrary result with the research did by Sulaiman et al. (2016) who studied about the effect of particle sizes in SFB with annular distributor. It found that particle size with different bed weights coincide with each other and deviate with other sizes of particles. Thus, apart from the minimum and maximum particle velocities, the interparticle space caused by usage of different sizes of particle may have a significant influence on the particle velocity as compared to the bed weight.
4) In term of bed weight in SFB with mesh-type distributor, it did not significantly influence the minimum superficial air velocity needed to get the particles fluidized initially as the bed weight increased. Another interesting finding is that, even though the bed weight increased, the particles velocity of heavier bed weight still exponentially increased. Thus, when processing particle with more bed weight, SFB with mesh-type distributor exhibit superiority because it need less energy to get the particles fluidized.
5) Generally observed that overall particles velocity of different particle densities are decrease as the bed weight increase. However, the effect of particle density will only exhibit significant effect to particles motion when it compared with particles that have similar size. It is found that, particle density influence to the superficial velocity needed to get the particle fluidized. Particle that has less density required less superficial velocity than the other particle that has more density.

6) The effect of particle density did not exhibit significant effect to particles motion when it compared with particles that have different sizes with different density. It is due to the heavier particles that experience stronger gravitational force that influence more superficial air velocity required to get the particles fluidized and cancel the effect of density in fluidization of the particles. Thus, it can be suggests that the effect of density will not occurred when processing multi-sizes particles in a SFB with-mesh type distributor.

Thus, one of the future researches that can be done for the study are listed as follow:

1. Evaluate the hydrodynamics of air velocity in mesh-type distributor in order to gain more insight into the behavior of airflow to the bed from the distributor.
2. Conducting experiment with more variant of particle sizes and particle densities to understand how the effect of particle density occurs to different size of particle.
3. Also, future research could be further analyzed about the utilization of wire mesh with different geometries as air distributor in SFB. Improved technique of PIV and more measurements should be done to obtain higher accuracy of particle velocity
4. Study of the variation of bed pressure drop in SFB with mesh-type distributor.

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