EFFECT OF PARTICLE DENSITY ON PARTICLE MOTION

OF A SWIRLING FLUIDIZED BED WITH MESH-TYPE DISTRIBUTOR

TO IMPROVE THE EFFICIENCY OF FLUIDIZATION PROCESS

THESIS

Submitted to International Program
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AUTHENTICITY STATEMENT

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Yogyakarta , 2nd September 2016

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ABSTRACT

Since its first development, fluidized bed had been used to a wide range of industrial application that involve chemical and mechanical processes. Numerous conventional fluidized beds have been developed including centrifugal fluidized bed, vibro-fluidized bed, tapered fluidized bed, spouted fluidized bed, etc. However, there are several shortcomings of these conventional fluidized beds that become the challenges of efficiency in processing materials. Further, these shortcomings affect the quality of fluidization in relation to moving parts, particle mixing, pressure drop, hydrodynamics, and limitation in using variety particle sizes. Thus, a new technology of fluidized bed was introduced. Swirling Fluidized Bed (SFB) is a recent technology on fluidized bed developed by researchers that acknowledged as current best options in the industry as this type of fluidized bed able to provide better quality of fluidization, such as, no moving parts in the process, uniform motion of particles influence to excellent particles mixing, reduces elutriation, lower pressure drop, and allows application of variety particle sizes. SFB has several variants of bed distributor; the most popular one is SFB with annular distributor. As it develop, it is found that high level of bed pressure drop is become major drawbacks of the current SFB with annular distributor. Thus, a new variant of air distributor is introduced, since air distributor in SFB hold a key role in distributing gas into bed column in which responsible for fluidization of the particles. There has been no published experimental study on the particle motion or behavior especially particle velocity of SFB with mesh type distributor. Therefore, an experimental study of the particle motion and velocity in SFB with mesh-type distributor is needed to fulfill this gap. The experiment was conducted in a laboratory scaled SFB with Mesh-type Distributor and wire mesh with 2.8mm^2 size is used in this experiment for the distributor. 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. The results exhibit that SFB with Mesh-type distributor provided advance improvement than annular distributor in term of efficiency. SFB with Mesh-type distributor needs less superficial velocity to get the particles fluidized despite the increasing bed weight, thus lower bed pressure drop is produced for the fluidization process as the output.

Keyword: Fluidization, Swirling Fluidized Bed, air distributor, PIV, particle study.

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CHAPTER I

INTRODUCTION

1.1. Background

In the early era of industrialization, the utilization of chemical and mechanical tools was discovered in order to develop a better technology for Industrial processes. Breakthrough on method to improve the existing chemical and mechanical processes is needed in order to reduce production cost and improve product yield. Numerous industrial processes involve intimate relation between solid particles and liquid or gas. In order to have a good operation in processes, a tool that provide higher heat and mass transfer rates is needed, and fluidized beds were considered as the best solution for it.

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 affect the quality of fluidization in relation to move 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 rows 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).

Therefore, the present study is intended to extend the previous researches on SFB by using different type of distributor in purpose to improve the efficiency of fluidization process by reducing the high level of bed pressure drop and the superficial velocity needed to have the particles fluidized. There has been no published experimental study on the particle motion or behavior especially particle velocity of SFB with mesh type distributor. The significance in acquiring comprehensive information of another variant of SFB could lead to supporting the design and manufacturing of the swirling fluidized bed when it is to be scaled up to the commercial unit.

1.2. Problem Statement

Swirling Fluidized Bed (SFB) has many advantages that able to overcome the shortcomings of conventional fluidized bed. Numerous researches on SFB with variety of distributors has been widely studied on various aspects of its operation, but it is founded that high-pressure drop across the distributor is one of major drawbacks of current distributor designs. 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. Most of researchers conduct study on the various aspects of the operation of SFB with annular distributor. There is limited study on the operation of SFB with mesh-type distributor. Furthermore, no published experimental literatures are available for the analysis of the particles velocity in SFB with mesh-type distributor.

Hence, from the information explained above, the problem statement for this study will be: How is the fluidization process of SFB with Mesh-type distributor in relation to the particle density, bed weight, and particle size based on the experimental study conducted in a laboratory scale SFB with Mesh-type Distributor and how is the performance differences with SFB having an annular distributor.

1.3. Research Objective

Based on the written problem statement, the objectives of the present study are as follows:

1. To investigate particle motion in a SFB with Mesh-type distributor in relation to its particle density by mapping the trajectory of the bed particles.
2. To study the effect of bed weight and particle size on the performance of fluidization process in SFB with mesh-type distributor and investigate its differences with the performance of SFB with annular distributor.

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.

1.4. Scope of the Research

The scopes of the research are as follows:

1. Using an accurate and effective visualization technique and velocity measuring technique, Particle Imaging Velocimetry (PIV). Besides, an overall study of the swirling fluidized bed is accomplished in order to understand the relation between the velocity/trajectory and other parameters related to the fluidized bed.
2. The experiment conducted in a laboratory scale SFB with Mesh-type Distributor
3. The experiment focused in the study of particles motion in relation to the selected parameters used in the research

1.5. Benefits of the Research

An experimental study on SFB with different variant of distributor is important to provide information on how different variant of distributor works. Although SFB has been studied for years, the technology has not been fully developed, and some problems may occur such as unexpected material wastes, unstable heat transfer, corrosion, erosion, etc. (Lee and Liu, 2004). Thus, it could be a reference in designing the next variant of distributor in SFB with better operation and fluidization result. This could also contribute to the design of the scaled-up model SFB for industrial applications.

1.6. Systematic Writing

Specific systematic writing is applied in order to present the thesis comprehensively, the systematic used is as follows:

CHAPTER I **PRELIMINARY**

This chapter contains the background study of the problem, formulation of the problem, problem definition, research objectives and benefits of the research.

CHAPTER II **LITERATURE REVIEW**

This chapter contains the analysis on the result of studies that have been done previously that has connection with the research undertaken. It also contains basic concepts and principles needed to solve the research problems, the basic theoretical basis to support the study to be conducted.

CHAPTER III **RESEARCH METHODS**

This chapter contains the object of the study, required data regarding the study, experiment setup and tools, the research flow chart and Gantt chart.

CHAPTER IV **DATA COLLECTION AND PROCESSING**

This chapter describes the data collected during the experiments and processing of such data by a predetermined method of analysis results.

CHAPTER V **DISCUSSION**

This chapter discusses the results of research in the form of graphs concerning quantitative and statistical results of the experiment to answer the research objectives.

CHAPTER VI **CONCLUSSION AND SUGESTION**

This chapter contains a brief and precise statements derived from the results of the research and discussion to answer the problem. Advice were made based on author's experience and consideration, addressed to researchers in similar fields, who want to continue and develop the conducted research.

CHAPTER II

LITERATURE REVIEW

2.1. Inductive Study

Since its first development, fluidized bed has been used wide range of industrial applications that involve chemical and mechanical processes. Numerous conventional fluidized beds have been developed including centrifugal fluidized bed, vibro-fluidized bed, tapered fluidized bed, spouted fluidized bed, etc. (Howard, 1989). However, there are several shortcomings of these conventional fluidized beds that become the challenges of efficiency in processing materials. Further, these shortcomings affect the quality of fluidization in relation to moving parts, particle mixing, pressure drop, hydrodynamics, and limitation in using variety particle sizes. Thus, a new technology of fluidized bed was introduced.

Swirling Fluidized Bed (SFB) is a recent technology on fluidized bed developed by researchers to overcome the shortcomings of conventional fluidized bed. As mentioned by Amonsirirat et al. (2011) SFB provide upgraded features of conventional fluidized bed that are able to provide better quality of fluidization, such as, no moving parts in the process, uniform motion of particles influence to excellent particles mixing, reduces elutriation, lower pressure drop, and allows application of variety particle sizes. As it developed, several variants of bed distributor in SFB were invented. Bed distributor (air distributor) in SFB is one of the key parameters that affect the successful operation of fluidized beds, since it holds a key role in distributing gas into bed column in which responsible for fluidization of the particles.

Started by Spiral Distributor introduced by Ouyang and Levenspiel (1986) that inspired to the development of the popular Annular Distributor, which later improved by Shu et al. (2000). Ouyang and Levenspiel (1986) proposed a spiral distributor for swirl motion. They evaluated and compared the characteristics of this distributor, such as pressure drop, quality of fluidization and heat transfer coefficient with the sintered plate distributor. Just like the annular distributor, spiral distributor was made of overlapping vanes, shaped as sectors of a circle with a gap between the vanes. However, there is no report of the angle of vanes inclination. Shu et al. (2000) later studied the hydrodynamics of another version of swirling fluidization in toroidal fluidized bed reactor that using a distributor consisting of angled blades in an annular ring, which matched with the findings of Sreenivasan and Raghavan (2002).

Sreenivasan and Raghavan (2002) studied the hydrodynamic characteristics of fluidized bed with annular spiral distributor. The distributors were made by placing inclined vanes at an angle of 12° with the horizontal over an annular region with the help of outer and inner holders made of Plexiglas. Based on the experiment conducted, they have reported that the superficial velocity required for stable swirl motion is higher for higher bed weight. Furthermore, it found that there is an increase in bed pressure drop with airflow rate in stable swirl regime, and suggested the effect of wall friction as the reason. To extend these findings from, an analytical model for the prediction of hydrodynamic characteristics of SFB was proposed by Vikram et al. (2003) to further study the dynamics of bed pressure drop in SFB.

According to the findings of Vikram et al. (2003), the swirl velocity increases linearly and bed pressure drop increases parabolically with the superficial velocity. They reported that the vane angle has a considerable influence on the bed's characteristics such as bed pressure drop and swirl motion velocity, while the effect of cone angle is negligible. They further reported that swirl velocity as well as bed pressure drop decreases with increase in vane angle. 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 with conventional fluidized bed, in SFB the bed pressure drop in swirl mode increases with air velocity, as the bed pressure is proportional to centrifugal weight of the bed (Sreenivasan and Raghavan, 2002).

Even though, there is an analytical model for the prediction of the hydrodynamics behavior of the bed including, the pressure drop and angular velocity of particles was developed by Vikram et al. (2003) and Raghavan et al. (2004), however, these analytical models are used as an approach for the prediction of the hydrodynamic behavior of SFB with annular distributor. Till now, there has been no published experimental study on the particle motion or behavior especially particle velocity of SFB with mesh type distributor. The significance in acquiring comprehensive information of another variant of SFB could lead to supporting the design and manufacturing of the swirling fluidized bed when it is to be scaled up to the commercial unit.

For instance, in the application of coating, the velocity of the particle and the liquid spraying rate are very important for the design of optimized condition for the fluidized bed. However, without proper setting, the liquid spraying rate may exceed the rate of particle motion, and thus may cause the coated particles to collide before the liquid completely dries and thus agglomeration of particles will occur. In addition, SFB with different distributor also perform different operation. Different distributor will have different airflow rate distribution with one another in order to get the particles fluidized.

Therefore, an experimental study of the particle motion and velocity in SFB with mesh-type distributor will assist the realization of commercial SFB unit by providing more information and understanding of the particle hydrodynamic characteristics in this variant of SFB. Besides, the experimental result in the present study could be used as reference to compare the performance of SFB with mesh-type distributor to the other variants of SFB. This would be beneficial to provide more options for the industry in further development of commercial SFB unit.

2.2. Deductive Study

2.2.1. Fluidization

Fluidization is a process in which solids (particles) are caused to behave like a fluid by blowing gas directed upwards through the distributor. Particles become fluidized when an upward-flowing gas imposes a high enough drag force to overcome the downward force of gravity. The drag force is the frictional force imposed by the gas on the particle; the particle imposes an equal and opposite drag force on the gas as shown in Figure 2.1. Thus, as a particle becomes fluidized, it affects the local gas velocity around it due to these drag forces. But, not every particle can be fluidized. The behavior of solids particles in fluidized beds depends mostly on their size and density.

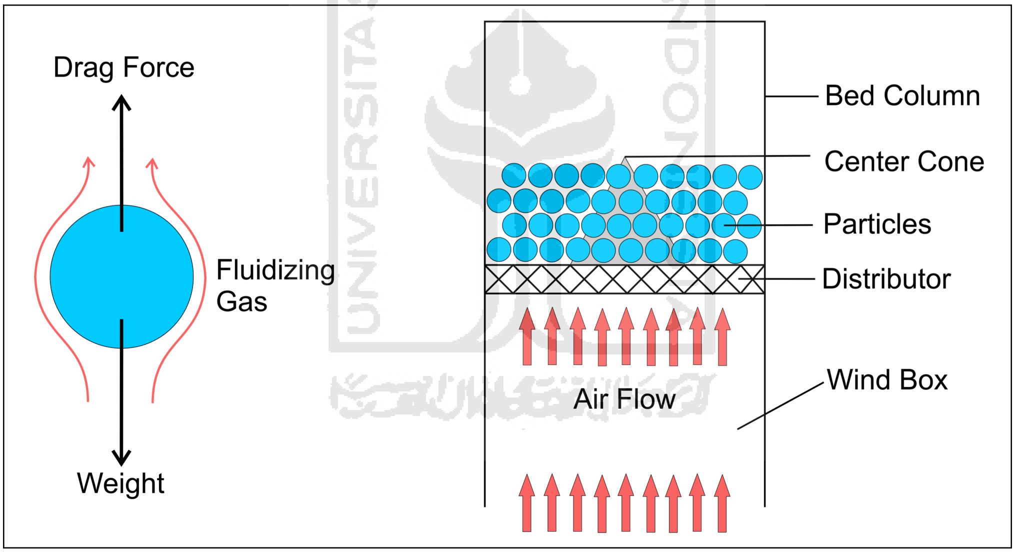


Figure 2.1 Illustration of fluidization process and drag force on particle

A careful observation by Geldart (1973) provides a method of classification which particles are classified into four groups: Geldart Groups A, B, C and D. The characteristics of each type have different behavior to one and another. Geldart Group A tends to be aeratable and fluidize well. Geldart Group B tends not to undergo smooth fluidization, and bubbles form at the onset of fluidization. Geldart Group C is considered cohesive as it almost always experiences significant channeling during fluidization. Geldart Group D is considered spoutable which have lower gas requirements than standard fluidized beds. It difficult to fluidize in deep beds and it can be formed in a spouting motion. A spouting bed is a type of fluidized bed in which the gas moves primarily through the center of the bed (Cocco et al., 2014).

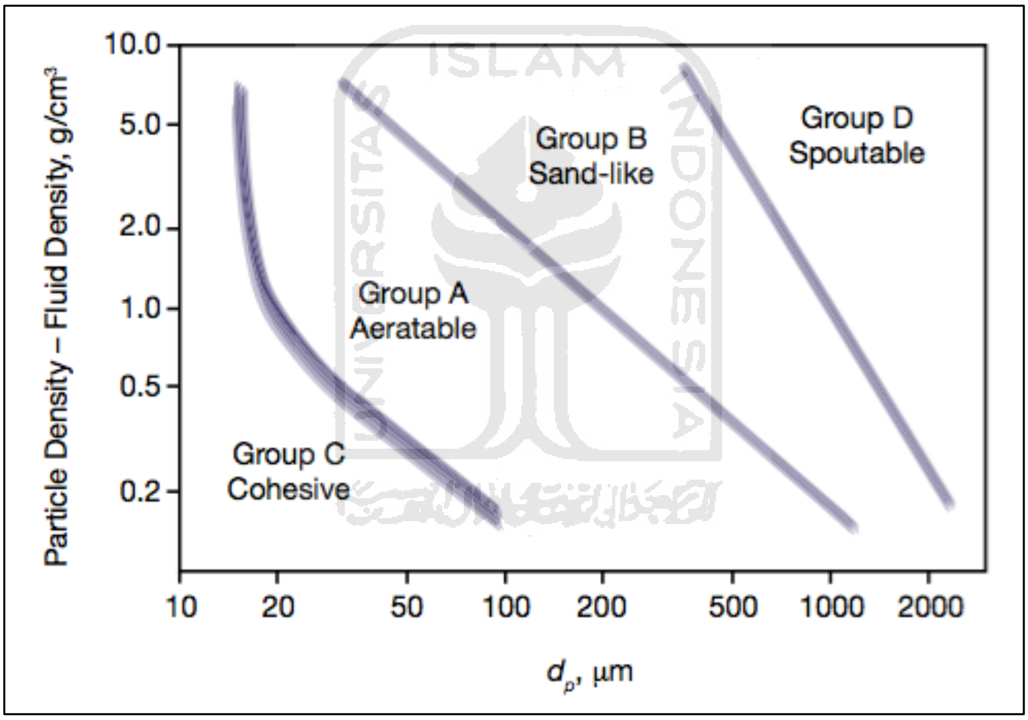


Figure 2.2 Geldart's particles classification according to fluidization properties

2.2.2. Fluidized Bed

Fluidized beds technology has operated commercially since the 1920s, beginning with the advent of the Winkler coal gasifier in Germany. Fluidized catalytic cracking units (FCCUs) for the production of high-octane gasoline and fluidized-bed reactors for making phthalic anyhydride was debuted in the 1940s. Today, about three-quarters of all polyolefins are made by a fluidized bed technology. Fluidized bed is the next generation of the previous reactors utilized in the industry such as packed-bed and stirred-tank reactors (Cocco et al., 2014). Typically, Fluidized beds are more challenging to design, build and operate than the previous types because it is prone to erosion and particle attrition caused by the moving particles. Solids losses can result in significant operating costs, especially when the solid particles are an expensive catalyst. Furthermore, a scale up of fluidized beds can be difficult.

Despite these challenges, fluidized beds offer three distinct advantages over previous technologies, which are, superior heat transfer, the ability to easily move solids like a fluid and the ability to process materials with a wide particle size distribution. Fluidized bed provides a huge benefits that able to overcome the limitations of pervious reactors, in addition, the heat-transfer in a fluidized bed can be five to ten times greater than that in a packed-bed reactor. Moving particles, especially small particles, can transport heat much more efficiently than gas alone. Thus, by seeing the superiority of using fluidized bed could outweigh the challenges, especially for processes requiring catalyst circulation and superior heat.

2.2.3. Swirling Fluidized Bed

For years, a lot of works has been done as effort in develop fluidized bed technology which able to fluidize variety of particle types efficiently and able to provide superior performance over conventional fluidized bed. These efforts resulted in the development of a lot of different fluidized beds such as centrifugal fluidized bed, circulating fluidized bed, vortexing fluidized bed, rotating distributor, rotating with static geometry, toroidal fluidized bed, swirling fluidized bed, conical swirling fluidized bed, etc. (Vinod Kumar and Raghavan, 2011).

Swirling Fluidized Bed (SFB) is a recent effort of researchers in order to overcome the shortcomings of conventional fluidized bed. Many superior features offered by SFB such as, no moving parts, uniform mixing, better quality of fluidization, and lower distributor pressure drop, hence lower pumping power. (Sulaiman et al. 2016). Major difference between conventional fluidized beds and SFBs is in the distributor design. Distributor has an important role to distribute gas into bed column and affected the swirling motion of the particles. There are several methods in achieving swirling fluidization: secondary injection of fluidizing medium into the freeboard tangentially (Sowards, 1978), utilization of a distributor which provides inclined injection into the bottom of the bed (Paulose, 2006), and rotation of the distributor or rotation of the bed column (Sobrino et al., 2008).

Even though there are several methods used, the purpose is similar, which allowing gas enters into the beds that have two components of velocity: (i) the vertical component causes fluidization and (ii) the horizontal component causes swirling motion to the particles (Paulose, 2006). Many attempts have been made to develop better distributor for SFB. Virr (1958) reported the behavior of a shallow bed heat exchanger working on the swirling bed principle. Ouyang and Levenspiel (1986) proposed a spiral distributor to achieve swirl motion in SFB. Shu et al. (2000) studied the hydrodynamics of a toroidal fluidized bed (torbed) using fine particles and compared its performance to conventional beds. Sreenivasan and Raghavan (2002) studied the hydrodynamic characteristics of fluidized bed with annular spiral distributor. Vikram et al. (2003) developed an analytical model for the prediction of hydrodynamic characteristics of swirling fluidized bed. Annular distributor with a central cone was used for this study. Recent works on SFB mainly used annular distributor on their research. Figure 2.3 shows the sample illustration of configuration in a SFB with annular distributor.

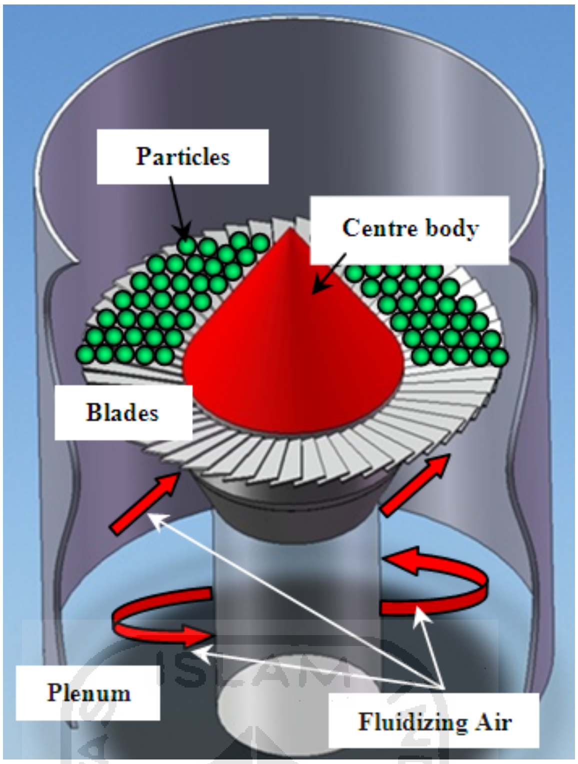


Figure 2.3 Illustration of configuration in a Swirling Fluidized Bed with Annular distributor

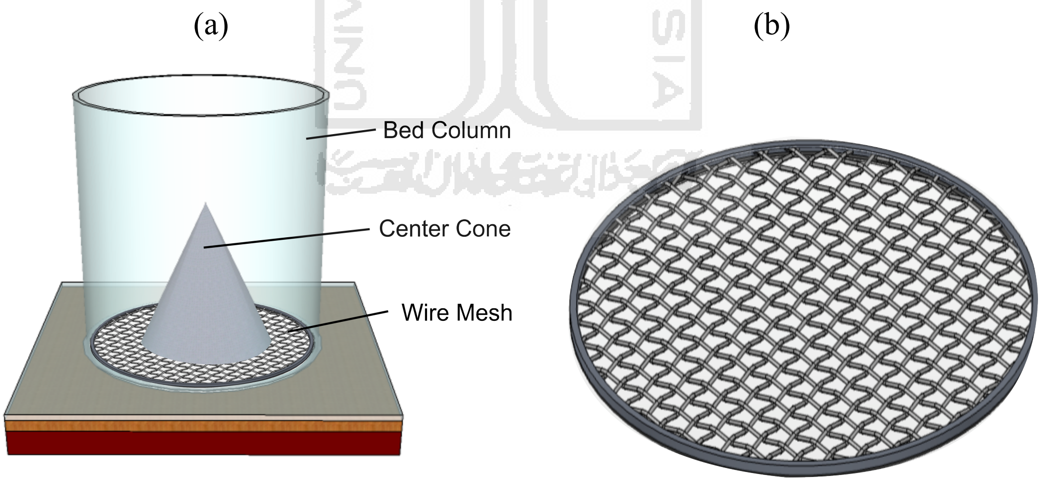


Figure 2.4 Illustration of configuration in a Swirling Fluidized Bed with Mesh-type distributor, (a) Mesh-type distributor with center cone, (b) Wire mesh

A. Working Principles

In SFB operation, an inclined injection of gas will be introduced through the distributor into the bottom of the bed. The jet of gas entering the bed will have two components of velocity, which are vertical component and horizontal component. The vertical component causes fluidization and the horizontal component causes swirling motion to the particles. Sreenivasan and Raghavan (2002), reported that there are typically four regimes of particles motion can be found in SFB with increasing gas velocity: (i) the first regime is known as fixed bed in which a state of particles are not fluidized because the gas drag force is not sufficient to overcome the weight of particles, (ii) the second regime is called bubbling regime, as gas velocity increases, minimum fluidization will be reached with gas bubbles form above distributor, (iii) at this state, gas velocity begin higher, the regime involves the formation of dune and wave motion, and started form two zones which are swirling zone and static zone.

The particles are moving around in the swirling zone and entering the boundary of static zone while at the boundary of static zone, particles are moving away, which reduces the bed height. This causes wave motion of the particles, (iv) On further increasing gas velocity, dune formation is starting to disappear and swirling region become wider until finally achieved steady state swirling motion of particles. This forth regime is applicable only to shallow bed. The changes on different regimes of fluidization are illustrated below in Figure 2.4.

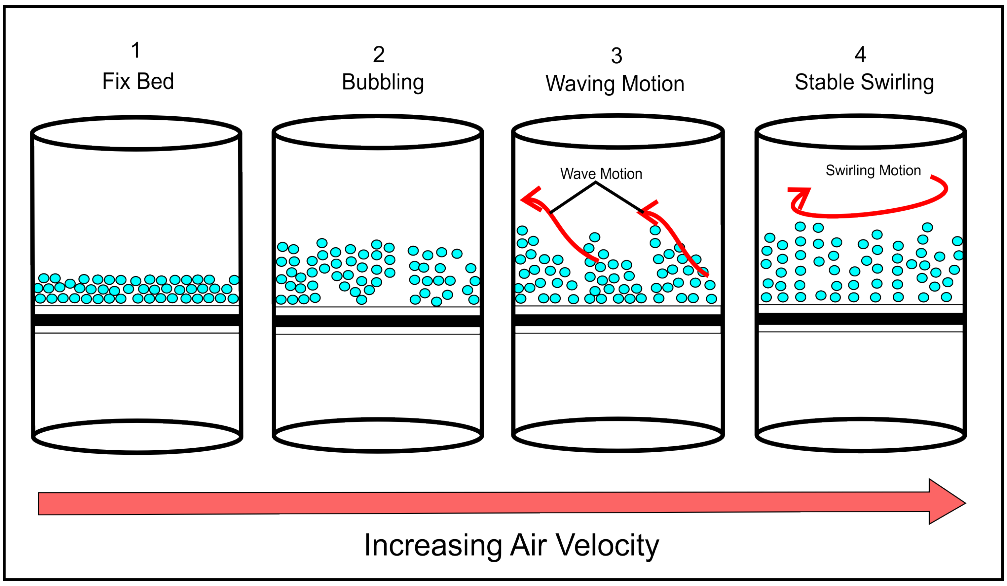


Figure 2.5 Illustration of changes on different regimes of fluidization

In the case of when bed height is higher and deep enough, two layers of regime will be formed where a little continuous swirling layer is observed happened at the bottom of the bed and vigorously a huge continuous bubbling layer happened at the top of the bed. The illustration of two layers of the regime is shown below in Figure 2.5.

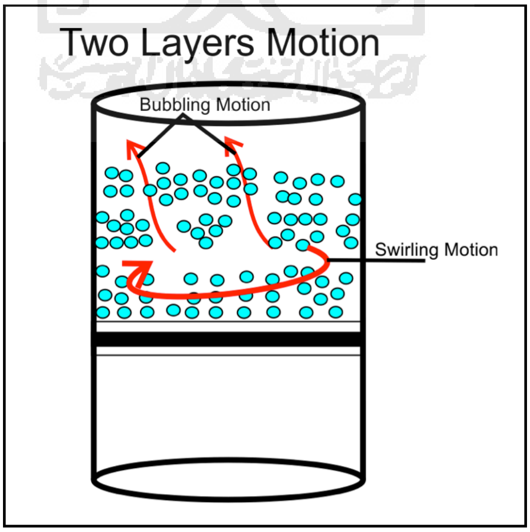


Figure 2.6 Illustration of two layers of regime

B. Advantages

SFB offer superior features that 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). In the operation of SFB, it minimizes the axial momentum transferred to the particle with a larger fraction of momentum being transferred radially and tangentially. This increases the mixing of the particles and eventually increases the transport properties of the particles. The swirling motion enables gas velocity to be increased to high values with little elutriation. Furthermore, large particles in Geldart Group D, which are usually difficult to fluidize in a conventional fluidized bed can be effectively fluidized in SFB (Paulose, 2006).

C. Air Distributor

Air distributor in SFB holds a key role in distributing gas into bed column. It is one of the key parameters that affect the successful operation of fluidized beds is the type of distributor. It is known that the efficient and stable operation of a fluidized bed is sensitively controlled by the design of the distributor (Yang et al., 2011). The review from previous works on SFB has shown that the type of distributor design significantly affects the operation of fluidized bed in various aspects such as, performance characteristics, fluidization quality, air flow dynamics, solid pattern and mixing caused by the direction of air flow through the distributor and bed pressure drop (Shukrie et al., 2016).

D. Bed Pressure Drop

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 with conventional fluidized bed, in SFB the bed pressure drop in swirl mode increases with air velocity, since the bed pressure is proportional to centrifugal weight of the bed (Sreenivasan and Raghavan, 2002). Previously, Shu et al. (2000) studied the hydrodynamics of another version of swirling fluidization in toroidal fluidized bed reactor, which matched with the findings of Sreenivasan and Raghavan (2002). Further research was conducted with the concern of the pressure drop of the bed.

Paulose (2006) studied more details about the hydrodynamics of SFB particularly on the percentage area of opening, angle of air injection and the percentage of the useful area of the distributor. The distributor pressure drop was found to be decreasing with increase in the percentage area of opening. In addition, Batcha and Raghavan (2011) studied the pressure drop in relation with the particles size found that larger particles had lower pressure drop and high bed load increased pressure drop. Vinod Kumar et al. (2012) studied the variation of bed pressure drop in relation with various particles shape. In the experiment, he used 3 different particles, which are: (i) spherical particle, (ii) cylindrical particle, (ii) ellipsoidal particle. It is resulted that spherical particle bed gets fluidized late than other two. Since, the exposed area is the least for spherical particle, it requires a large airflow to generate enough drag force to balance the weight of the particles in order to get them fluidized initially. Thus, higher energy required influence higher-pressure drop in the case of spherical particle.

In the case of cylindrical particle, even though the exposed area is more than spherical particle, the two circular faces of the particle are ineffective as they are parallel to the flow and do not contribute much to total drag force. For ellipsoidal particle, it has largest exposed surface area compared to other two shapes, thus more force generated so that the get fluidized early.

E. Particle Velocity

Particle velocity of the swirling bed is also another important hydrodynamic characteristic, which must not be neglected, as it is one of the factors, which determine the design, and performance of the bed. Lee and Liu (2004) did a study on the bed expansion and analysis on the particle velocity in a swirling fluidized bed combustor cold model, which used the injection of secondary air for the creation of the swirl motion. It was found that the secondary air injection did not affect the bed expansion but increased the particle velocity. However, the particle velocity analysis was done based on the images taken from the wall side which does not really give much information regarding the angular velocity and swirl motion of the swirling particles.

An analytical model for the prediction of the hydrodynamics behavior of the bed including, the pressure drop and angular velocity of particles was developed by Vikram et al. (2003) and Raghavan et al. (2004). Vikram et al. (2003) assumed that the angular velocity of the particles remains constant across the bed height, which means the model cannot predict the variation of the angular velocity and pressure drop according to the bed height and radial distance. This model was further developed by Raghavan et al. (2004) who eliminated the lumped model used by Vikram but introduced two-dimensional model (axial and radial directions) which gave a more realistic prediction of the hydrodynamic behavior of SFB. However, these analytical models are used as an approach for the prediction of the hydrodynamic behavior of SFB with annular distributor.

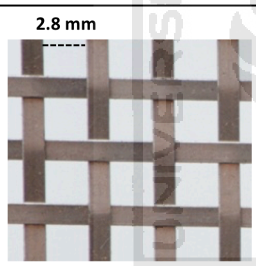
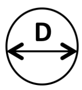
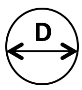
CHAPTER III

RESEARCH METHOD

3.1. Research Object

The object of this research is focused on particle study about its behavior in SFB with Mesh-type distributor related with selected parameters as shown in Table 3.1. The study was conducted by experiment in laboratory scaled Swirling Fluidized Bed with Mesh-type distributor that is provided by Laboratory of Mechanical Engineering in Universiti Teknologi Petronas, Malaysia.

Table 3.1. Parameters of experiment

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			

For this study, wire mesh with $2.8mm^2$ size is used in this experiment for the distributor. 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.

3.2. Required Data

According to the problem statement and research objectives, the research is performed by experiment. The kind of data that required in this research is defined as follows.

1. Primary Data

   The primary data of this research are the measurement data from the experiment and described as follows:

   a. Superficial velocity to get the particles fluidized.
   b. Bed pressure drop for the fluidization.
   c. PIV Imaging of the particles captured by using high-speed camera.
   d. Data obtained from the analysis in MATLAB software.

2. Secondary Data

   The secondary data of this research are derived from literature study related to problem solving of the research. The literature sources mostly were the previous studies on hydrodynamics of a swirling fluidized bed, bed pressure drop of fluidized bed, experimental studies on swirling fluidized bed, superficial fluid velocity, and Particle Image Velocimetry. The information related with the performance of SFB with annular distributor is used in this study to investigate its differences with the performance of SFB with Mesh-type distributor.

3.3. Experiment Setup

To conduct the experiment, a laboratory scale swirling fluidized bed with mesh-type distributor was set up. A wire mesh was arranged on inside bed column with a hollow mental cone placed in the center of the bed. A 20 cm diameter 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.

In setting the Particle Imaging Velocimetry (PIV) system, a high-speed camera, a halogen lamp, mounting support and computer were required. The high-speed camera that used was Phantom® ir300 manufactured by Vision Research Inc. as shown in Figure 3.1 and the specifications of the camera is summarized in Table 3.2.

Figure 3.1 Image of high-speed camera

Table 3.2 Specification of the high-speed camera

Maximum Frame Rate	6688fps at full revolution
Maximum Resolution	2048 x 2048
Sensor	Extended-range CMOS sensor
Image Depth	14-bit

The mounting supports which allowed imaging from the top of the bed for the camera was custom-made. The reason was that the available tripod could not be utilized due to the height of the bed, which was approximately 160 cm, and the direction of the camera view was from the top of the bed. Figure 3.2 illustrates the configuration of the whole equipment set up including the SFB with mesh-type distributor used for the experiment.

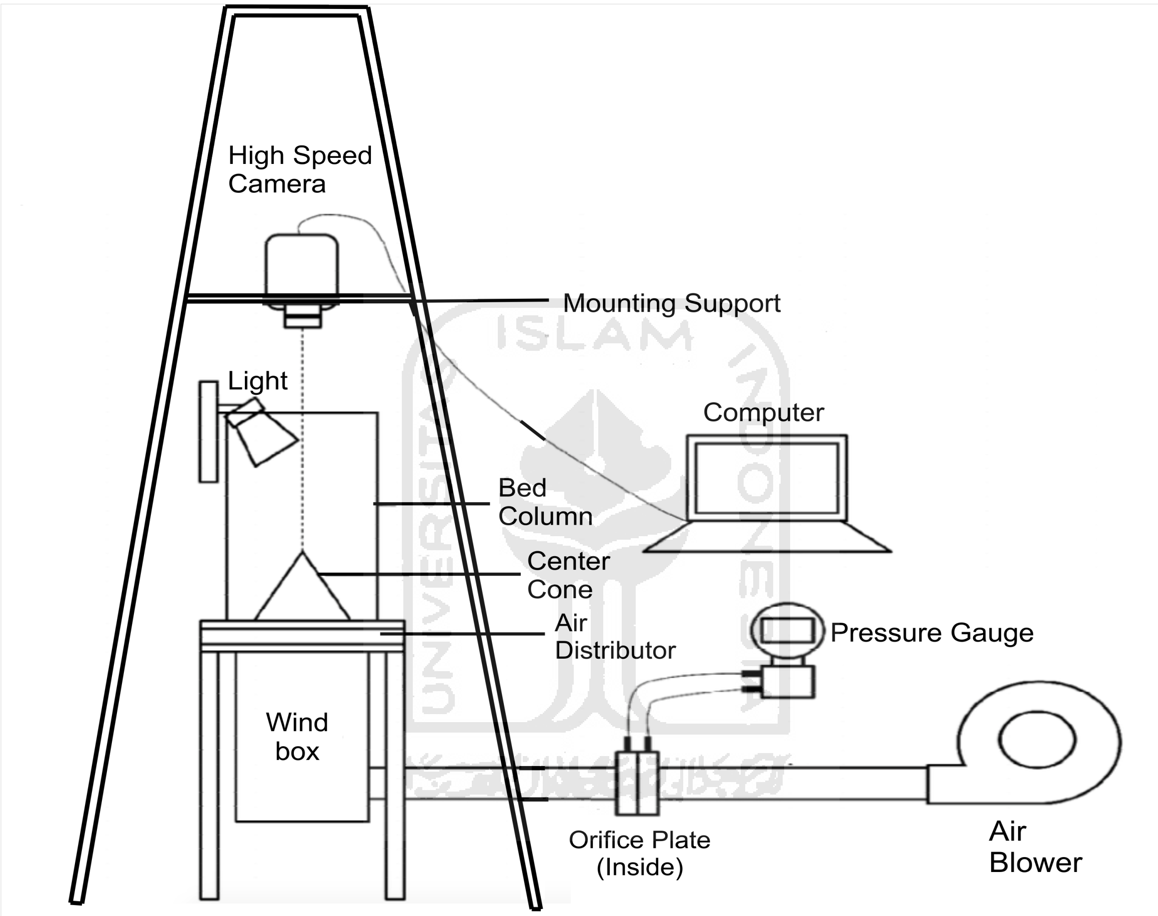


Figure 3.2. Schematic of the laboratory scale of swirling fluidized bed with mesh-type distributor

3.4. Experiment Technique

The working scheme of PIV can basically be broken down into four phases, which are seeding, illuminating, photographing and image processing. Each of these phases will be further discussed in next sections with relation to the experiment of this project.

3.4.1. Seeding

The particles flowing in the fluidized was in very high density, which increases difficulty in identifying the tracer particles. 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. Different mixture ratios of coloured particles were tested and Table 3.3 shows the final ratios used for each particle shape and size.

Table 3.3 Colors and ratios of the particles used

Particle	Colour	Ratio
6mm Particle	Grey (Tracer) : Black	1:4
6mm Particle	White (Tracer) : Black	2:3
4mm Particle	White (Tracer) : Pink	2:3
3mm Particle	White (Tracer) : Blue	2:3

3.4.2. Illumination

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 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 since it was reasonable to assume that circular motion of the particles was uniform.

By photographing half of the bed also could lead to increase the accuracy of experiment result. In the experiment, some particles could experience turbulent when flow regime become unsteady caused by the chaotic changes in flow velocity. Photographing 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. Therefore, a halogen lamp was used to illuminate the section from the top opposite of the bed section with angle adjusted as shown in Figure 3.3, to give the best illumination.

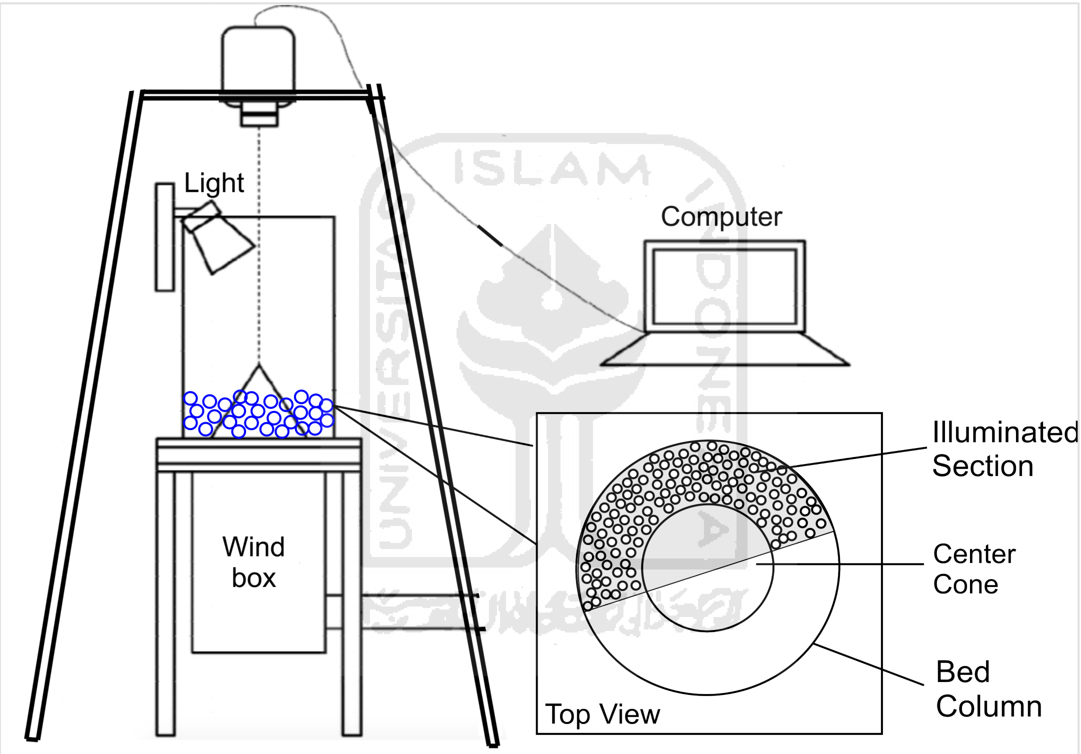


Figure 3.3 Illumination system for swirling fluidized bed

3.4.3. Imaging

After seeding the flow and adjusting the light angle, the high-speed camera recorded images of the flow. The optical axis of the camera lens must be perpendicular to the plane but it was not easy to set up the camera precisely. Therefore, calibration needed to be done to determine the parameters every time before taking the image. 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 acknowledged 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.

3.4.4. Image Processing

Image processing is the most important stage in PIV. 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. This was to determine how big a pixel in the image was or in other words, it was a process to transform the local camera coordinates (pixels) to the real physical world coordinate of the experiment by using the dimensions known in the image.

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. However, it was necessary to eliminate some “unusual” velocities in the image.

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. Signal-to noise ratio filter used information available in the correlation plane to quantify if the signal strength was "high" compared to the noise level. The global filter removed velocities, which were larger than a set threshold times, the standard deviation of the measured- velocity field while local filter excluded vectors, which were having much difference with the neighboring interrogation windows.

Since filters had eliminated some vectors, there were holes left in the velocity field. These holes could be filled by interpolation from the existing data such as the neighboring velocity near the holes. Then, next step continues to analyze the vector field from the image, after expected vector field earned, vector validation is necessary to ensure that it has good vectors in whole area of the field, it should aim for having only a very small amount of orange vectors (error vectors). After the expected field is achieved, a complete velocity field was obtained.

3.5. Equipment and Tools

The equipment and tools used to conduct this study are mainly provided by Laboratory of Mechanical Engineering in Universiti Teknologi Petronas, Malaysia. Equipment and tools that required in this study to support the present research are listed as follows:

1. Laboratory scale of Swirling Fluidized Bed (SFB) with Mesh-type Distributor
2. A High-speed camera
3. A Laptop that specifically use for photographed the fluidized bed
4. Mounting support for the camera
5. PVC Particle with 4 different size and density
6. A halogen lamp for illumination of fluidized bed
7. MATLAB software that run PIV program for analysis

3.6. Research Timeline

The timeline schedule of the research is shown by the Gantt chart in Table 3.4

Table 3.4. Gantt chart of the research timeline

No.	ACTIVITY \ WEEK	1	2	3	4	5	6	7
1	Preliminary Research Work	■	■					
2	Literature Review	■	■	■	■	■	■	■
3	Experiment Planning		■					
4	Image Acquisition		■	■				
5	Image Processing		■	■	■			
6	Data Analysis and Interpretation				■	■	■	
7	Report Writing				■	■	■	
8	Submission of Technical Paper							■
9	Oral Presentation							■
10	Submission of Report							■

3.7. Research Flowchart

The method of the research is schemed in a flowchart. The flowchart described the flow of the research conducted from the beginning until the end phase of the research.

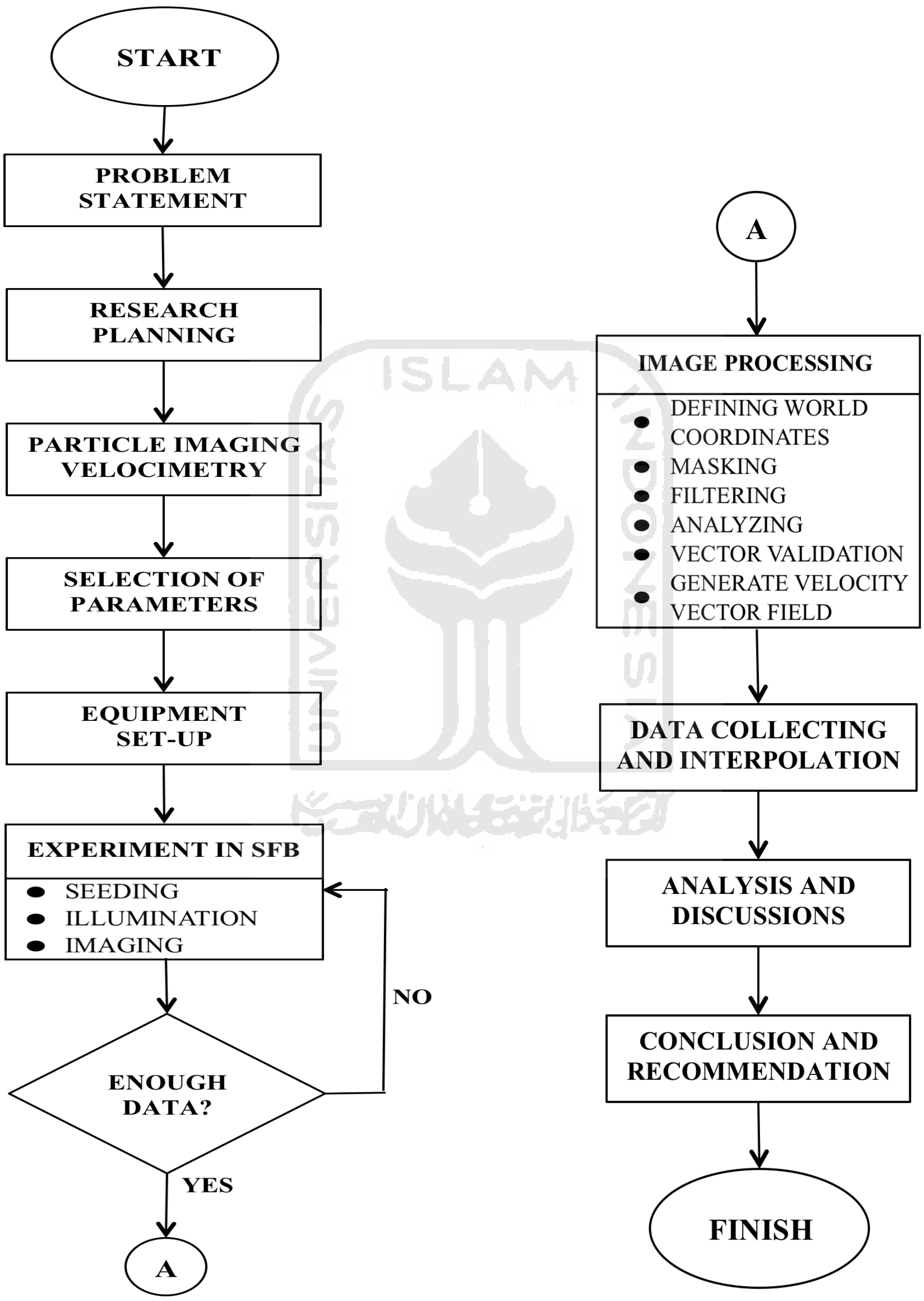


Figure 3.4. Flowchart of the research

CHAPTER IV

DATA COLLECTION AND PROCESSING

4.1. Data Collection

The data are collected for this research is obtained through experimental study. Approximately 1200 images of each particle with increasing bed weight and pressure drop have been taken. Good quality images are chosen to be processed with PIVlab program in MATLAB software and 10 repetitions have been carried out to increase the accuracy of the measurement. Figure 4.1 shows an example of the imaging of particles motion for one of the experiments with 4mm diameter sphere particles with 2.99 g/cm^3 particle density of 750 g bed weight, with 63 mmH_2O and 76 mmH_2O pressure drop across the orifice plate.

(a) (b)

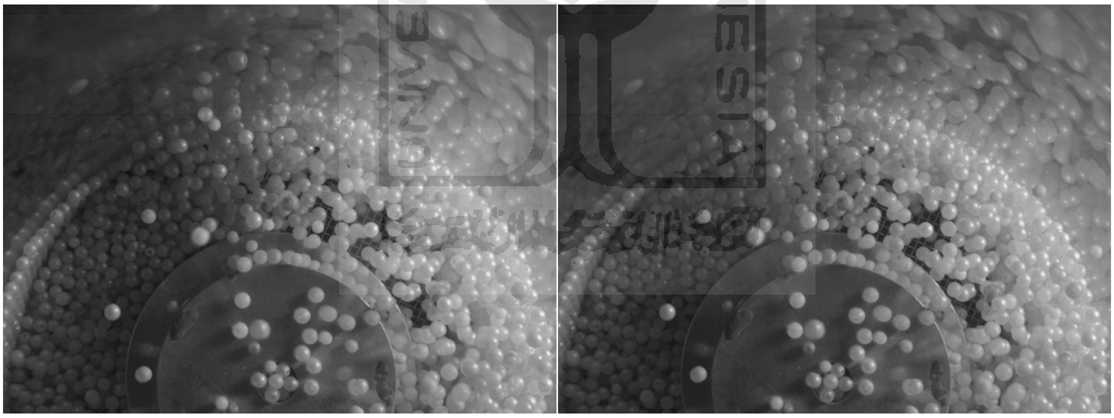


Figure 4.1 Particles motion of one of the experiment with 63 mm H_2O (a) and 76 mm H_2O (b) pressure drop.

4.2. Particle Imaging Velocity Analysis in MATLAB Software

Images of each particle with increasing bed weight and pressure drop have been taken. Good quality images are chosen to be processed with PIVlab program in MATLAB and 10 repetitions have been carried out to increase the accuracy of the measurement. Figure 4.2 shows an example of particles image for one of the experiments with 6mm diameter sphere particles with 2.21 g/cm^3 particle density of 750 g bed weight.

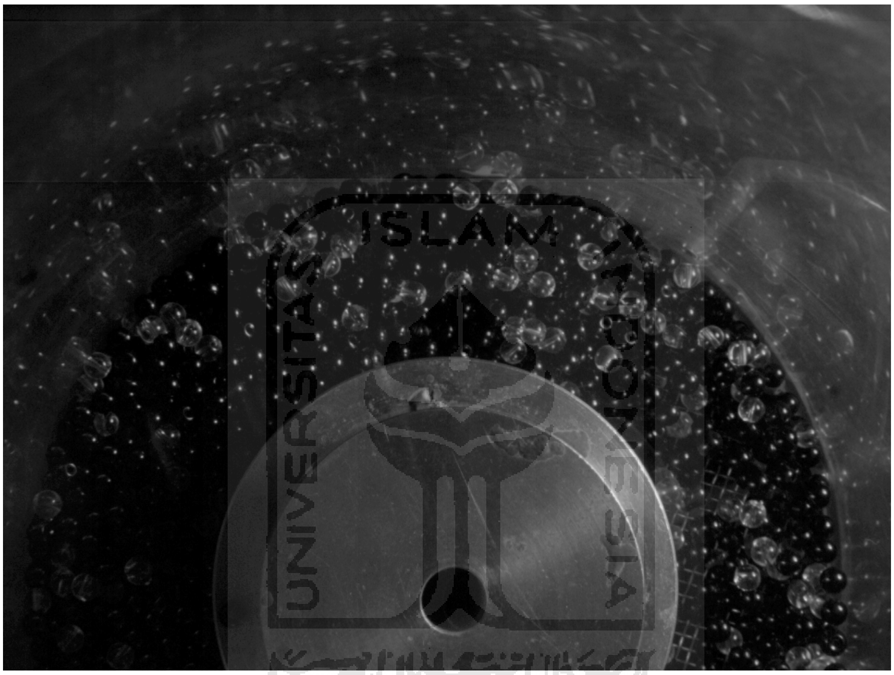


Figure 4.2 Particles image of one of the experiment with 6mm diameter sphere particles with 2.21 g/cm^3 particle density of 750 g bed weight

After the image was inserted in Matlab software, masking the unexpected area is needed to ensure the desired area is set for analyzing the vector field. Figure 4.3 shows the masking area in Matlab and followed by Figure 4.4 that shows the filtering for the image to be processes for analyzing the vector field.

Figure 4.3 example of masking are of the particle image

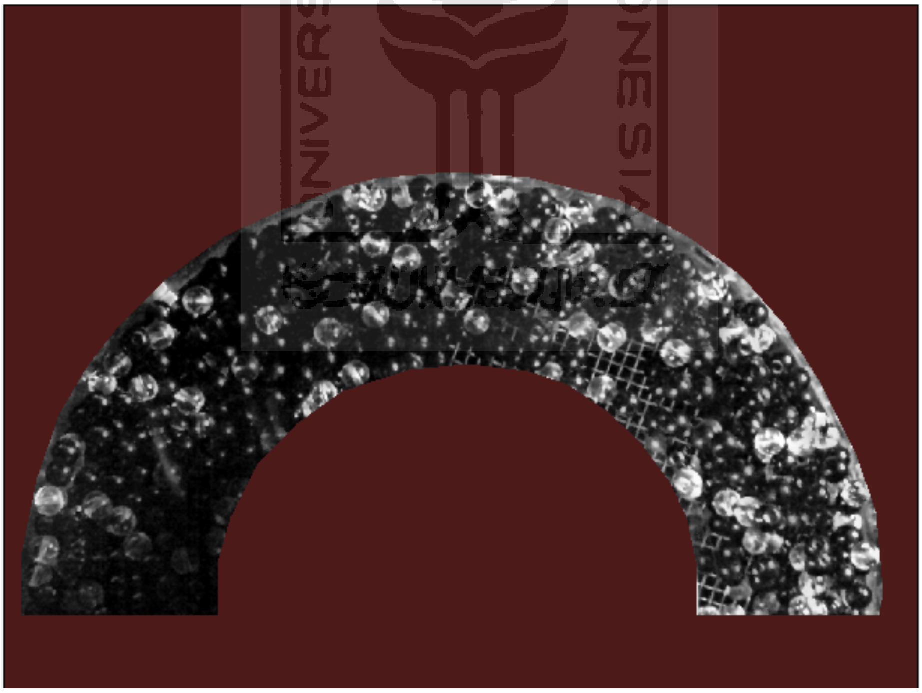


Figure 4.4 example of filtering phase of the particle image

After the image is ready, the analysis is conducted to generate the expected vector field. Figure 4.5 shows the analysis process and the vector field that generated.

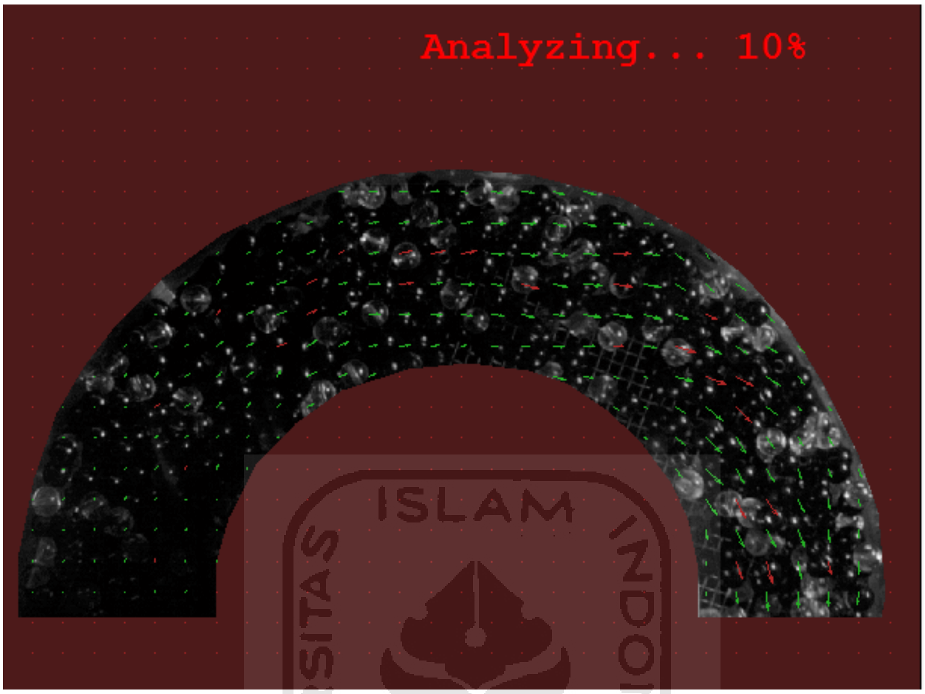


Figure 4.5 Vector field generated from the analysis

After the analysis done, vector validation is conducted to eliminate scattered velocity data in order to ensure the field that has very minimum amount of error vector. Figure 4.6 shows the velocity data that represent the vector field that generated from the analysis.

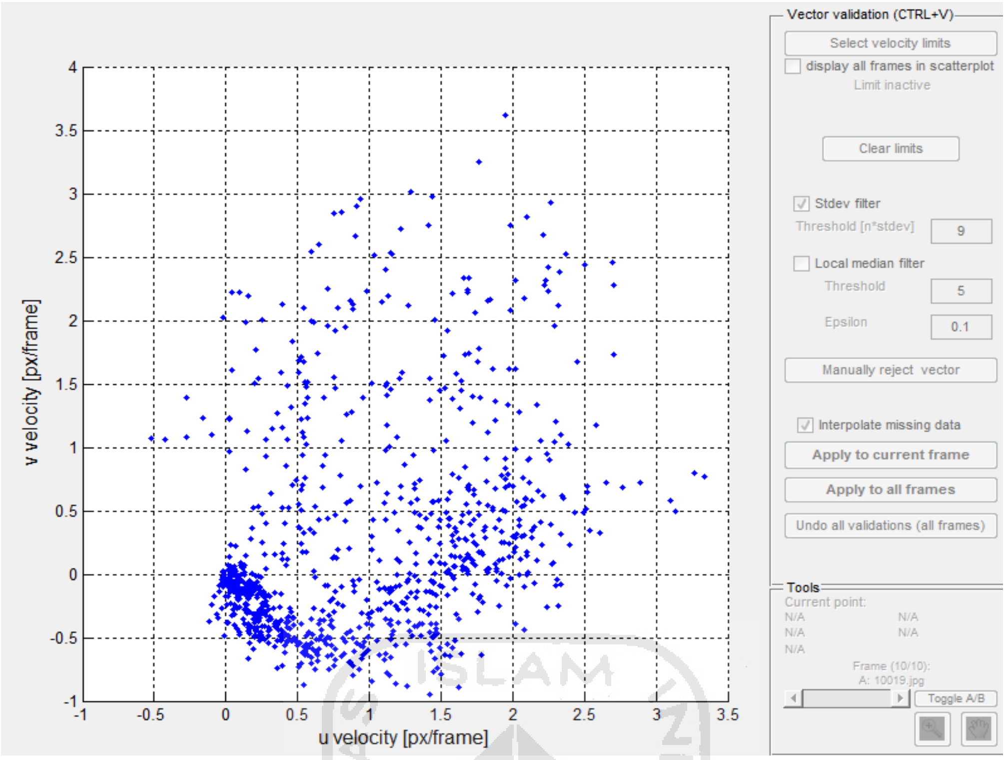


Figure 4.6 Example of velocity data of vector field generated from the analysis

Then, finally the expected velocity field is achieved to show the particles motion in fluidized bed that represented by the vector trajectory and color bar.

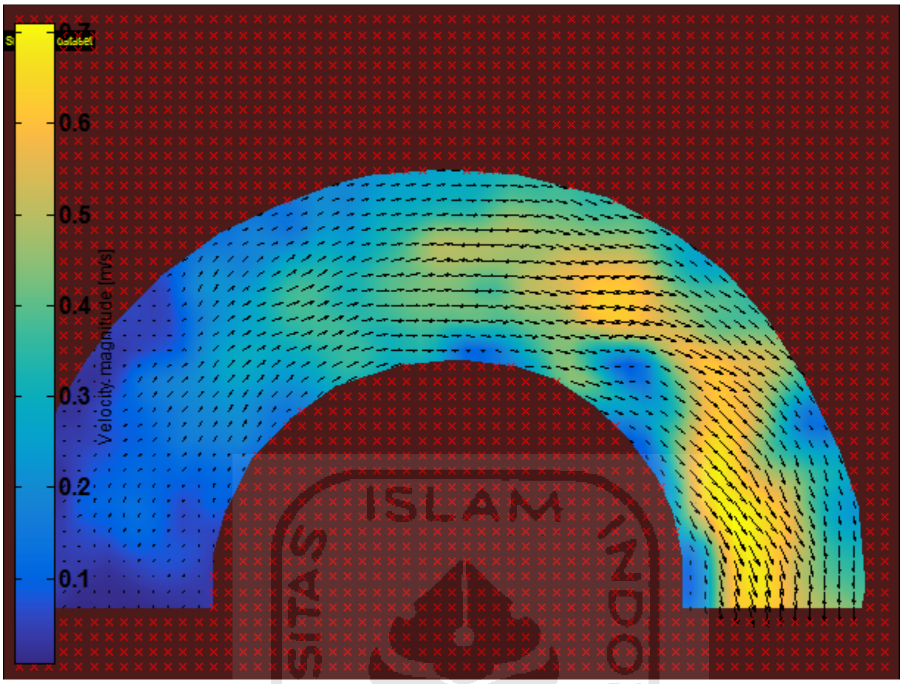


Figure 4.7 Example of velocity field generated from PIV MATLAB analysis

4.3. Post-processing of PIV Analysis

Before images are being analyzed, superficial velocity and air jet velocity are determined from the equations as discussed in Section 4.3.1. The velocity field interpretation is discussed in section 4.3.2 to explain how is the velocity profile is obtained. Section 4.3.3 discuss further about the obtained velocity profile of particles.

4.3.1. Superficial Velocity

In order to calculate superficial velocity when entering the bed, the airflow rate through the pipe had to be determined from the pressure drop in the orifice plate. Equation (4.1) was used to calculate the airflow rate referring to the dimensions of orifice plate as shows in Figure 4.7.

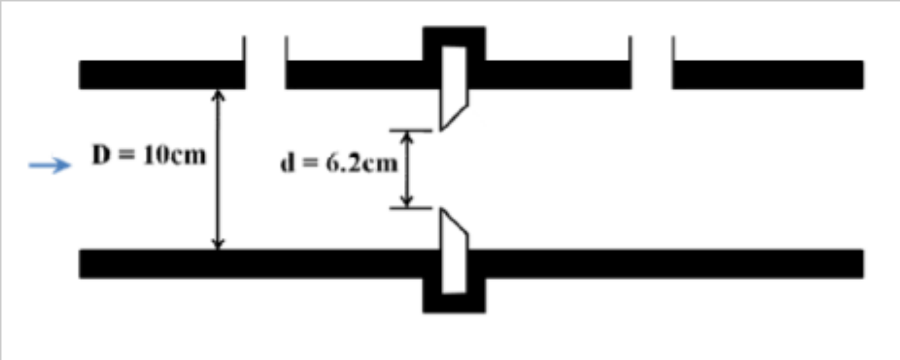


Figure 4.8 Dimensions of orifice plate

$$\boldsymbol{Q = A_0\, C_d \sqrt{\frac{2(P1 - P2)}{\rho(1 - \beta^4)}}} \qquad (4.1)$$

Where Q is the airflow rate through the pipe, A_0 is the cross-sectional area of the hole C_d is a constant which depends on the particular design of the orifice plate, $P1 - P2$ is the pressure drop which was recorded from the pressure gauge, ρ is the air density which was assumed to be 1.2 kg/m^3 and β is the diameter ratio d/D. Having airflow rate, superficial velocity, $V_{superficial}$ was calculated by dividing the airflow rate, Q with bed are, A_{bed}:

$$\boldsymbol{V_{superficial} = \frac{A}{A_{bed}} = \frac{Q}{\frac{\pi}{4}\,({D_o}^2 - {D_i}^2)}} \qquad (4.2)$$

The diameter of the bed column D_o is 20 cm, while the diameter of the center cone D_i is 10 cm.

4.3.2 Data plot of Velocity Field Interpretation

Velocity fields were generated from the PIV program and five particle velocities were averaged to obtain final velocities. Figure 4.9 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. The velocity field shows the particle trajectory and the color bar indicates the velocity in m/s unit.

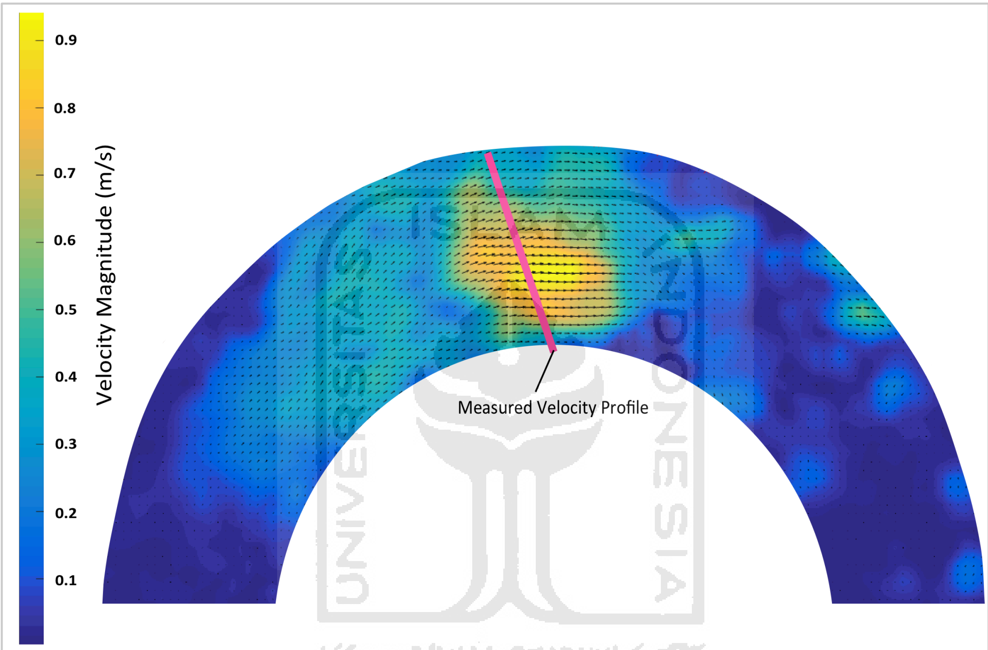


Figure 4.9 Typical velocity vector fields of particles

From the velocity field, it could be observed that particles are not moving uniformity, it shows that particles in some areas do not have velocity. It is due that, the particles at this time 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 measured in order to know the maximum number of U velocity in particular superficial air velocity. Figure 4.10 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.

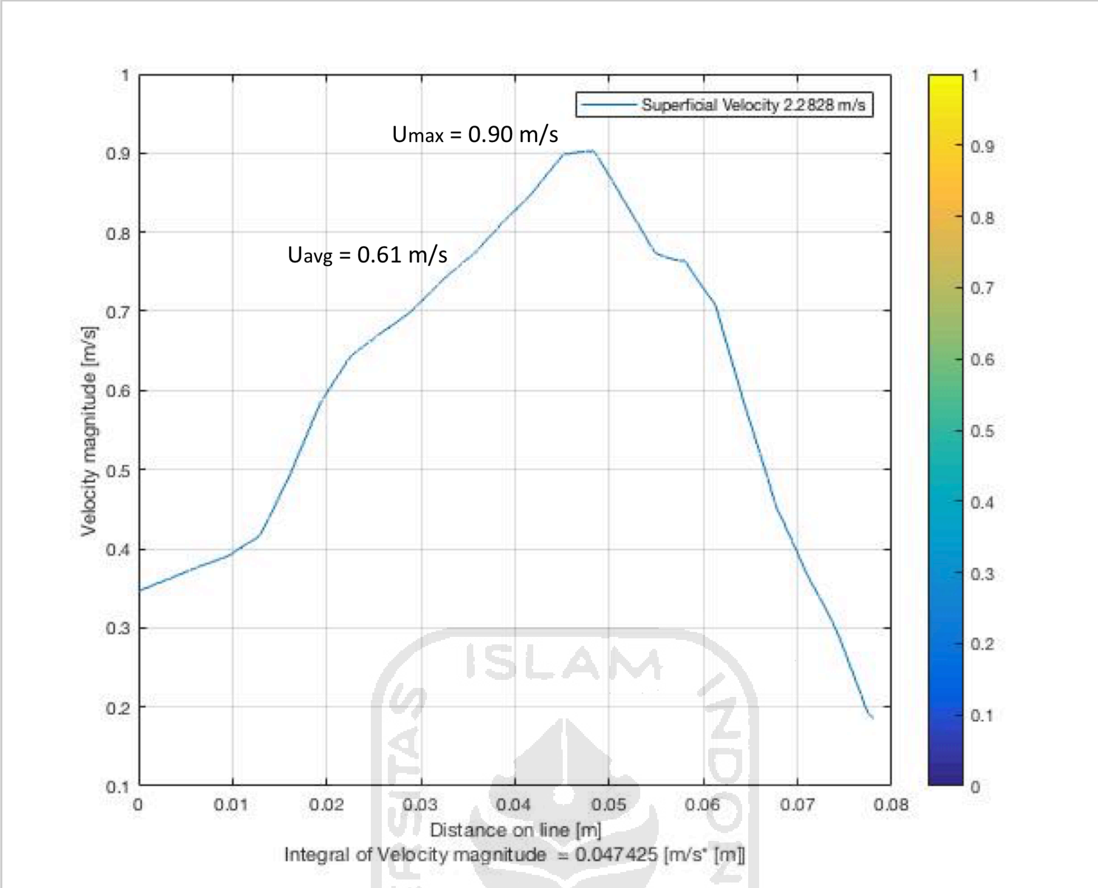


Figure 4.10 Graph of U-velocity of particles in the measured area

Different pattern of velocity could be obtained depending on which area is selected to be measured regardless of the superficial air velocity. The U-velocity of particles are 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 particle due its sensitivity to superficial air velocity and demonstrates the velocity profile of particles with increasing superficial air velocity. The velocity profile of 6mm diameter sphere particles with 2.21 g/cm3 density with increasing superficial velocity in 500g-bed weight is discussed in section 4.2.3.

4.3.3 Data plot of velocity profile of particles

Figure 4.11 shows the U-velocity of 6mm diameter sphere particles in 500g bed weight with increasing superficial air velocity. The graphs are obtained from the velocity field in each superficial air velocity. Each graph represents 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 increased as the superficial velocity increased.

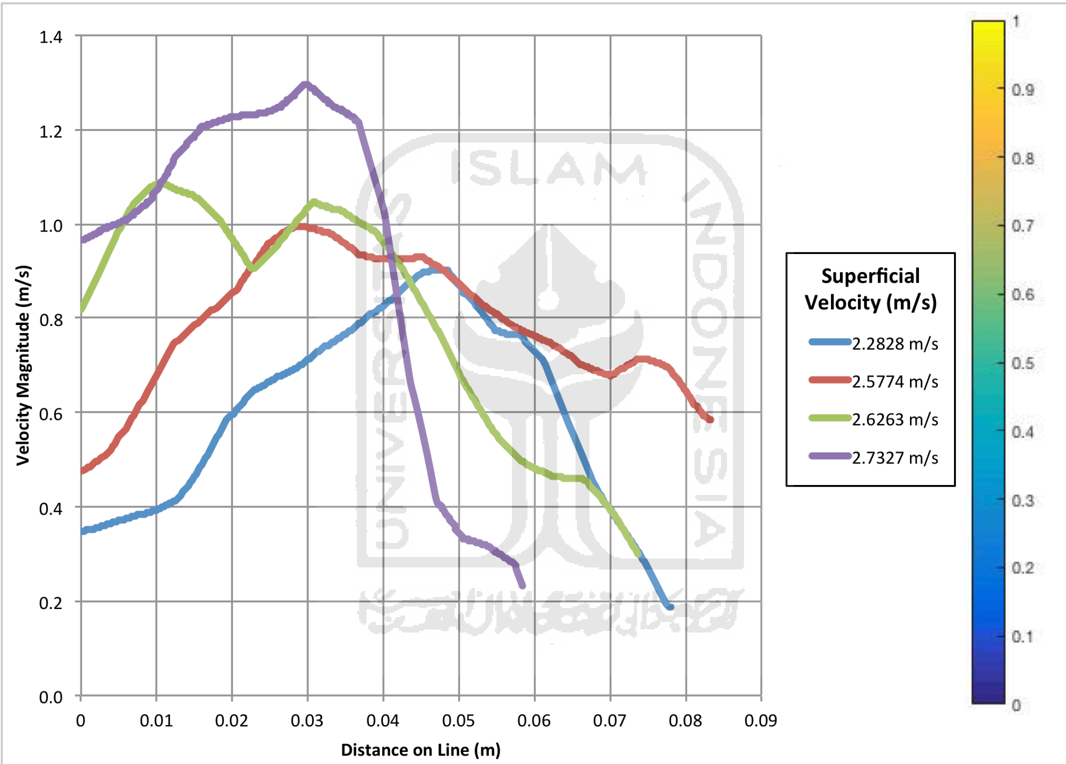


Figure 4.11 Graph of U-velocity of particles in the measured area with increasing superficial air velocity

Table 4.1 shows the velocity profile of 6mm diameter particles in 500g-bed weight with increasing superficial air velocity.

Table 4.1 Velocity profile with increasing superficial 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

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.

Since the study of SFB with mesh-type distributor is very new, there is no previous work that discusses about the hydrodynamics of SFB having mesh-type distributor. However, generally observed that particle motion in this variant of SFB is lack of uniformity. In velocity field that generated, there are some areas within the field where particles have no motion. Beside of the things that explain in previous paragraph, the distributor also has key factor that responsible for the particle motion.

CHAPTER V

RESULTS AND DISCUSSIONS

5.1. The Effect of Particle Size

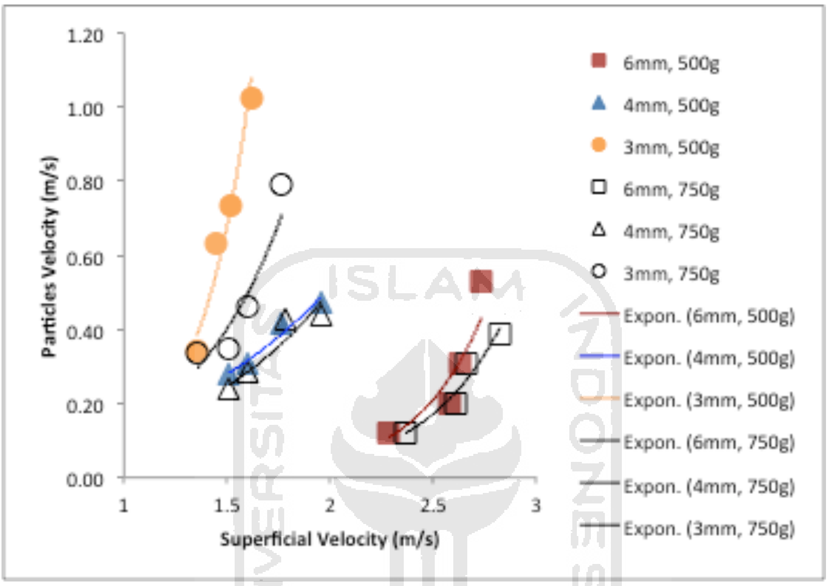


Figure 5.1 Variation of particle velocity for different spherical particle sizes

As shown in Figure 5.1 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 that 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 5.1, it is 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 5.1 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.

Thus, it can be 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.

5.2. The Effect of Bed Weight

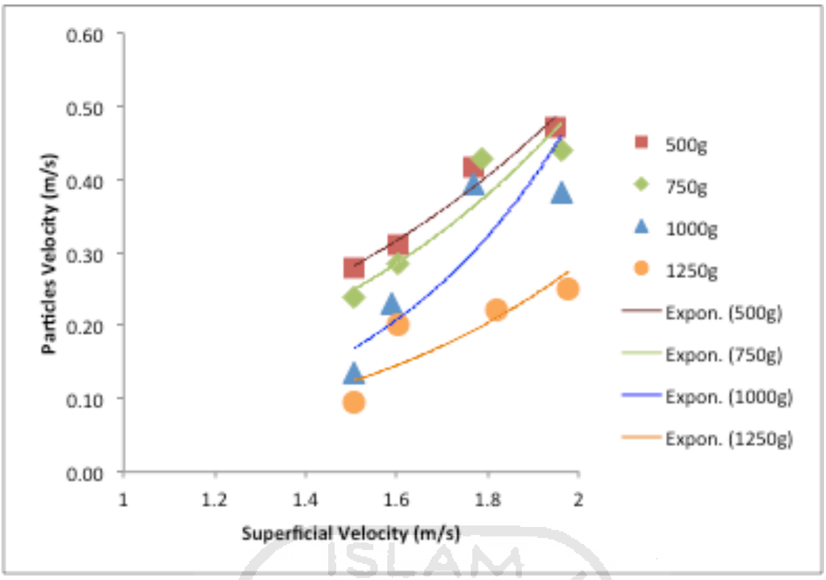


Figure 5.2 Variation of particle velocity for different bed weight of spherical particles

Figure 5.2 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 5.2 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. This reduced the swirling momentum from the jet air.

5.3. The Effect of Particle Density

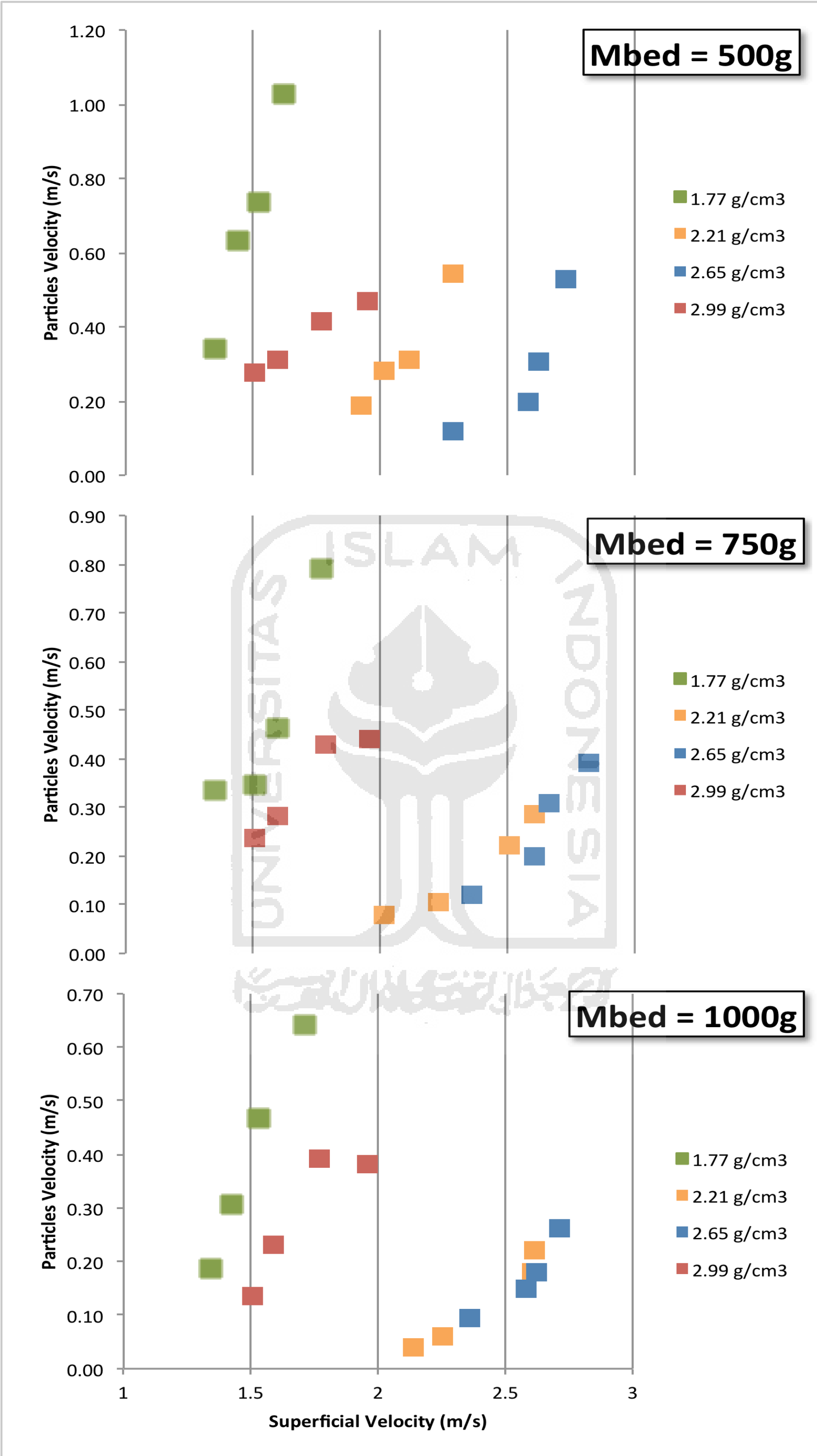


Figure 5.3 Variation of particle velocity for different particle density

Figure 5.3 shows the velocity of four particles with variation of density; 3mm*(1.77 g/cm3)*, 6mm*(2.21 g/cm3)*, 6mm*(2.65 g/cm3)*, 4mm*(2.99 g/cm3)*, at different superficial air velocities with bed weight between 500 g to 1000 g. From the graph, we can found clearly that, the particle velocity of all densities increased with air superficial velocity. Nevertheless, when the bed weight was increased, the variation of particle velocity decreased. This was due to the occurrence of constant bubbling described earlier in the bed weight discussion. However, an inverse relationship was predicted between the average velocity and density of the particles. A decrease in average velocity with density of the particles was referred to the particles weight.

Even though there are changes in the particle density, it does not have a significant influence on the minimum superficial air velocity for all particles as the bed weight increased. Similar to the trend in graph of Figure 5.1 that particle with different bed weights are coincide with each other, this was due to the superficial air velocity that does not have significant influence to the particle velocity as bed weight increased.

However, the effect of particle density will only exhibit significant effect to particles motion when it compared with particles that have similar size. The significant factors that affecting the fluidization are the bed material type and weight per unit cross-sectional area of the bed (Groot et al., 2002). The heavier particles experience stronger gravitational force; therefore addition superficial air velocity was required to cancel out density effect on complete fluidization of the bed (Naz et al, 2016). Thus, it will be very difficult to address the effect of particle density in the experiment from the graph above. Due to the limitation of available particles, for this analysis it only uses both 6mm diameter particles with different particle density.

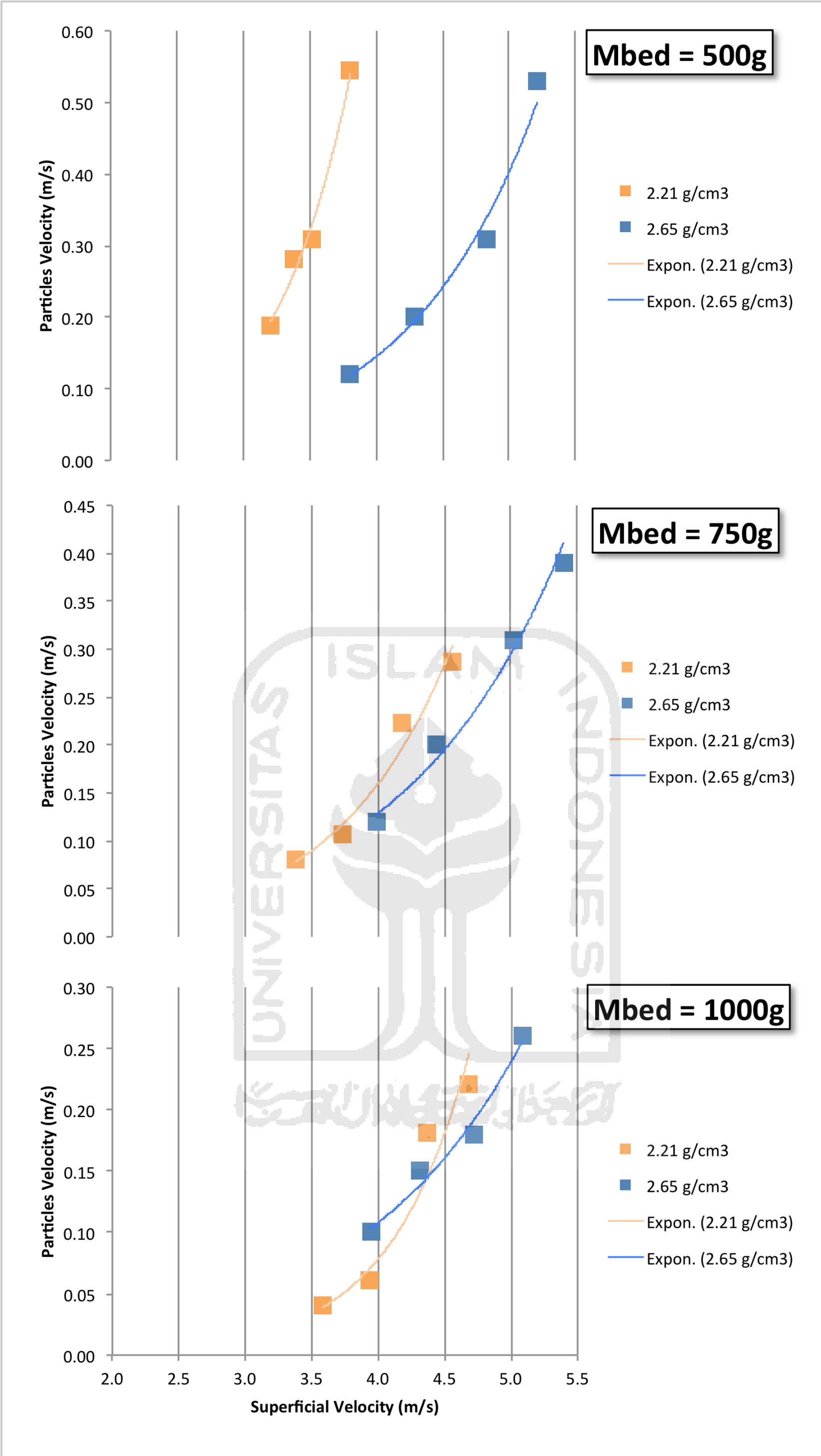


Figure 5.4 Variation of particle velocity for 6mm diameter particles with different particle density

From graph in Figure 5.4 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.

As shown in Figure 5.5 below, 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. 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.

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 suggested that the effect of density will not occurred when processing multi-sizes particles in a SFB with-mesh type distributor. However, a further study on the effect of particle density by using another particle with similar sizes and different density is needed to understand how the effect occurs to different particle size.

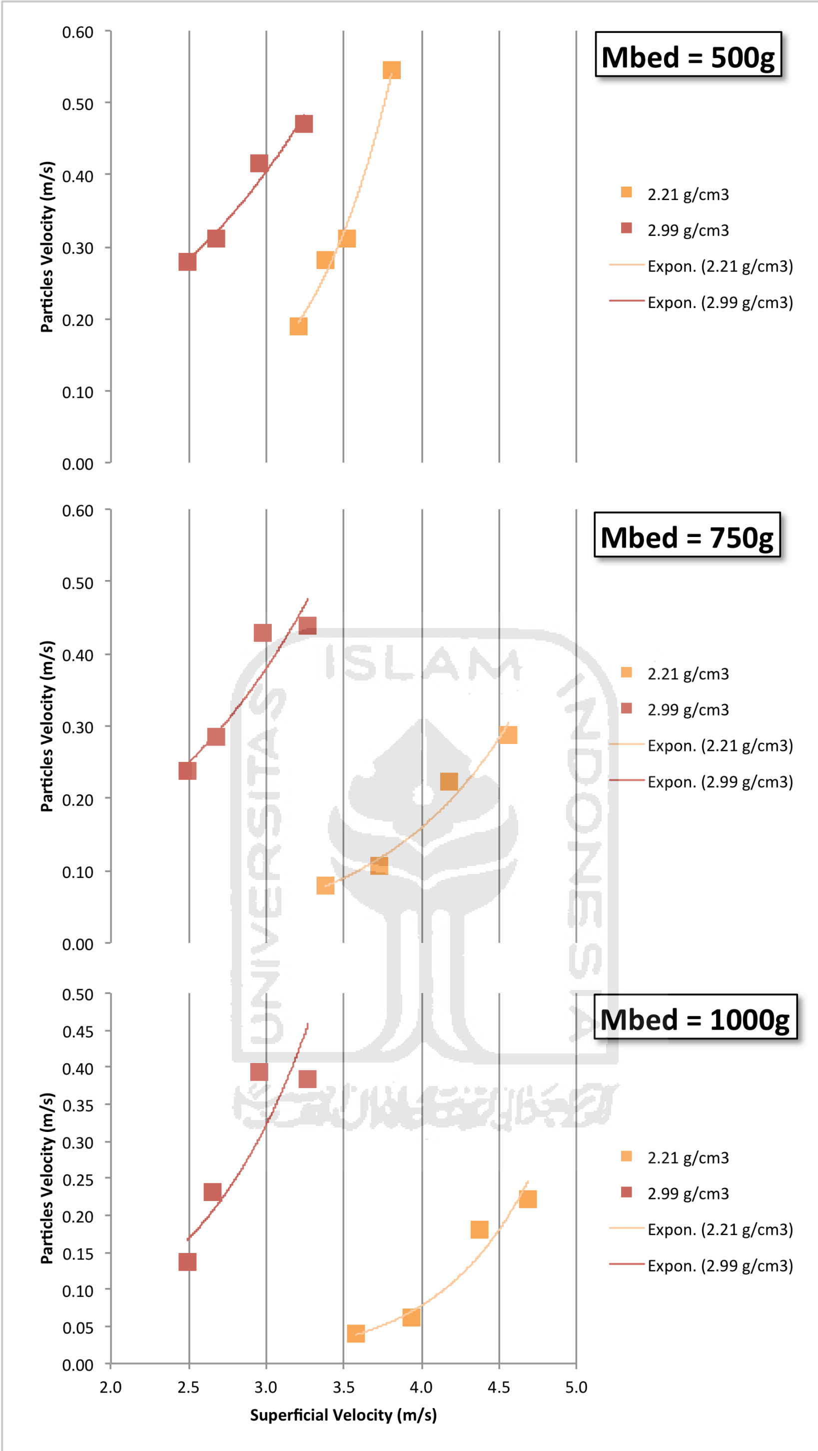


Figure 5.5 Variation of particle velocity for 6mm and 4mm diameter particles with different particle density

5.4. Comparison of Mesh-type and Annular Distributor

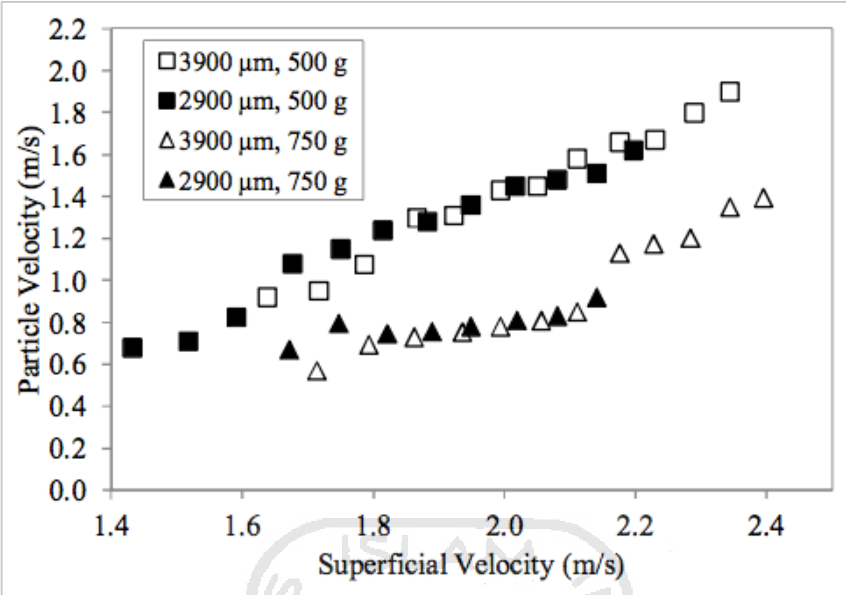


Figure 5.6 Variation of particle velocity for different particle size of spherical particles in annular distributor (Sulaiman et al. 2016)

In the research conducted 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 5.1, it found that particle size with different bed weights coincide with each other and deviate with other sizes of particles. This finding suggests that, apart from the minimum and maximum particle velocities, the inter-particle space caused by usage of different sizes of particle may have a significant influence on the particle velocity as compared to the bed weight.

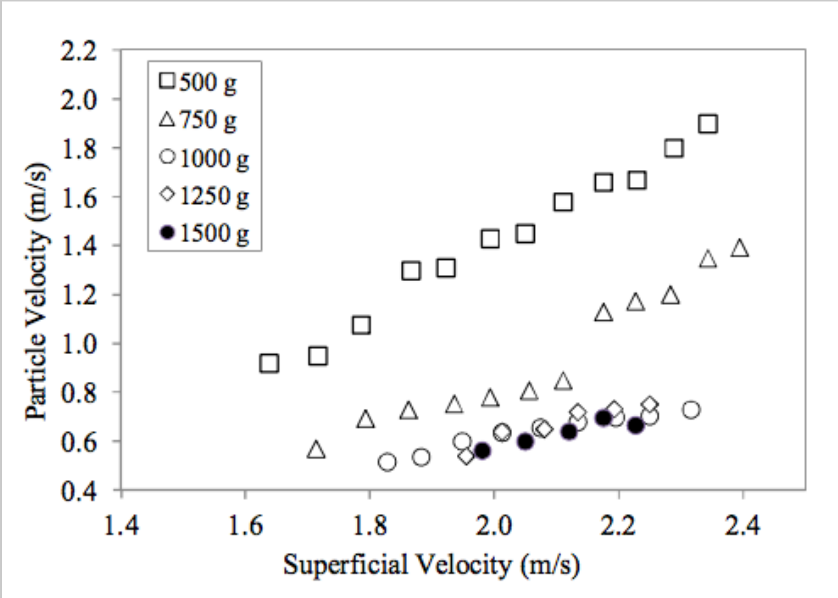


Figure 5.7 Variation of particle velocity for different bed weight of spherical particles in annular distributor (Sulaiman et al. 2016)

Another finding from graph 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.

CHAPTER VI

CONCLUSIONS AND SUGGESTIONS

6.1. Conclusion

Particle motion and the effects of several operating parameters such as air superficial velocity, bed weight, particle size and particle density on the particle velocity in a laboratory scale SFB with mesh-type distributor have been studied by using modified PIV technique. Particle trajectories and velocity are obtained from the velocity field generated from the PIV technique, which enable analysis of the graphs for different operating parameters studied. From the analysis, which has been conducted, following conclusions were obtained:

1. The decrease of particle velocity in response to increase bed weight and reduction of superficial velocity was in conformity with theories. An interesting finding suggested that when bed weight was increased, the particle velocity was less sensitive to the increase of superficial velocity.

2. It was 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 conducted by Sulaiman et al. (2016) who studied the effect of particle sizes in SFB with annular distributor. It is 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 was caused by the 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 was concluded 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 was decreased as the bed weight increased. 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. Thus, it can be suggested that using particles with less density is more recommended, since it will influence to less energy needed in processing the particles in SFB with-mesh type distributor.

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 suggested that the effect of density will not occurred when processing multi-sizes particles in a SFB with-mesh type distributor.

6.2. Suggestion

These findings will contribute to the development of distributor design in swirling fluidized bed to have better performance in its operation.

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

1. Study the hydrodynamics and analytical model in the operation of SFB with 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 further analyzed the utilization of wire mesh with different geometries as air distributor in SFB and improved technique of PIV and more measurements should be done to obtain higher accuracy of particle velocity

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