AERODYNAMICS OF A SWIRLING FLUIDIZED BED

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ABSTRACT

Swirling Fluidized Bed (SFB) is one of the fluidized bed systems that have potential to be widely used in the mineral processing, power generation and chemical industries. By using an annular bed and inclined injection of gas through the distributor in SFB it will archive a high performance in fluidization. A numerical simulation Computational Fluid Dynamics (CFD) and experimental work with Particle Image Velocimetry (PIV) has been used to investigate physical parameters that influence the type of plenum chamber, the distributor pressure drop and the uniformity of tangential velocity distribution. The study focused on the 60 blades distributor whereby the effect of two horizontal inclinations (12° and 15°) and tangential entry plenum chamber (single, double and triple). Three velocities component were analyzed; tangential velocity, radial velocity and axial velocity. In actual industrial applications, the axial velocity will create fluidization while the tangential velocity provides swirling effect. The presence of radial velocity can be explained as a consequence of centrifugal force generated by the swirling gas. The tangential velocity is the major velocity component in this study and it represents the velocity of the swirling air in the annular region of the bed. The uniformity of tangential velocity distribution and pressure drop is set as performance criteria and has been analyzed with statistical method; mean value, standard deviation & root mean square of difference (RMSD). The most significant finding in simulation configuration is the pressure drop of the distributor blade increased when a triple tangential entry plenum chamber along with horizontal inclination 15° has been applied which then create high tangential velocity. Only parameter for double tangential entry plenum chamber consists with horizontal inclination, 12° has been selected to validate with the PIV result. Comparison of the simulation result (CFD) and experimental data (PIV) are presented, and it is confirmed that good agreement is obtained.

ABSTRAK

Sistem terbendalir terpusar (SFB) ialah salah sebuah sistem terbendalir yang berpontensi untuk di gunakan secara meluas di dalam pemprosesan mineral, penjanaan kuasa dan industri kimia. Dengan aplikasi SFB yang berbentuk cecincin serta suntikan gas pada kecondongan pengedar ia mampu meningkatkan kecekapan di dalam sesebuah pembendaliran. Simulasi berangka iaitu kajian berangka berbantu komputer (CFD) dan kerja ujikaji dengan Particle Image Velocimetry (PIV) telah digunakan bagi membuat pengesahan parameter-parameter fizikal yang mempengaruhi jenis kebuk udara, susutan tekanan pengedar dan taburan keseragaman pada taburan halaju menyerong. 60 bilah pengedar di mana kesan terhadap dua kecenderungan mengufuk (12° dan 15°) dan kemasukan menyerong (satu, dua dan tiga) telah di kaji. Tiga halaju komponen telah di nilai iaitu halaju menyimpang, halaju jejarian dan halaju paksi. Dalam aplikasi perindustrian sebenar, halaju paksi akan mewujudkan pembendaliran manakala halaju menyerong akan menghasilkan kesan pusaran. Kehadiran halaju jejarian dapat di lihat apabila terhasilnya daya empar akibat dari gas yang terpusar. Dalam kajian ini, halaju menyerong merupakan halaju utama dan ia mewakili halaju udara yang berpusar dalam ruang kebuk cecincin. Dengan menggunakan kaedah statistik (min, sisihan piawai & perbezaan punca kuasa dua (RMSD)) keseragaman pada taburan halaju menyerong dan susutan tekanan menjadi kriteria utama dalam pengukuran prestasi, Penemuan yang paling penting dalam konfigurasi bersimulasi ialah susutan tekanan bilah pengedar telah meningkat apabila kebuk udara pada tiga ruang kemasukan menyerong dengan kecondongan mengufuk 15° telah mewujudkan halaju menyerong yang tinggi. Hanya kebuk udara pada dua ruang kemasukan menyerong dengan kecondongan mengufuk, 12° telah dipilih bagi mengesahkan keputusan ujikai PIV. Perbandingan yang amat baik di antara data simulasi (CFD) dan keputusan ujikaji (PIV) telah di capai dan di persetujui.

CONTENTS

LIST OF SYMBOL

A	–	cross-sectional area of the bed
AV	–	axial velocity
D_P	–	internal diameter plenum chamber
D_I	–	internal diameter tangential entry
g	–	gravitational acceleration
m	–	mass of particles
P	–	pressure
P_1	–	pressure at the facet average
P_r	–	pressure reference
R_D	–	radius of distributor
R_C	–	centre conical base radius
RV	–	radial velocity
TV	–	tangential velocity
VM	–	velocity magnitude
v_r	–	radial velocity
v_θ	–	tangential velocity
v_z	–	axial velocity
v	–	free stream velocity
v_c	–	centre velocity

Greek Symbols

μ	–	kinematics viscosity
ρ	–	density
ρ_f	–	fluid density
ρ_p	–	density of particles

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CHAPTER I

INTRODUCTION

Fluidized beds were been used in many chemical process industries are involved with gas-solid processing. When process gas passes through the bed, the force must be large enough to fluidize the bed weight. Then the particle normally will be fluidized and be having properties and characteristic of a liquid. This technique is truly compatible in industrial processes such as combination, gasification of solid fuels, drying of particles, particle heating, oxidation, metal surface treatments and catalytic and thermal cracking (Howard, 1989). Different type of bed particle required a containing vessel with porous base through which the gas processing can be exerted to the bed.

One of the recent developments in providing a variant in fluidized bed operation is the SFB, which provides swirling motion inside the bed apart from fluidization (Gupta and Sathiyamoorthy, 1999). In contrast with conventional fluidization, in SFB the fluidizing medium enters the bed at an inclination to the horizontal directed by a suitable design of a distributor (Wellwood, 1997).

Currently, various configurations are available in accordance to bed geometry, centre bodies, fraction of open area, gas flow rate and so on. Several modifications in fluidized beds have been considered by various researchers to overcome those problems, achieve better contact between gas and solid phases such that the transfer rates are improved and purposed a generating swirl flow in a bed of solids (Harish Kumar and Murthy, 2010). A typical SFB is depicted in Figure 1.1.

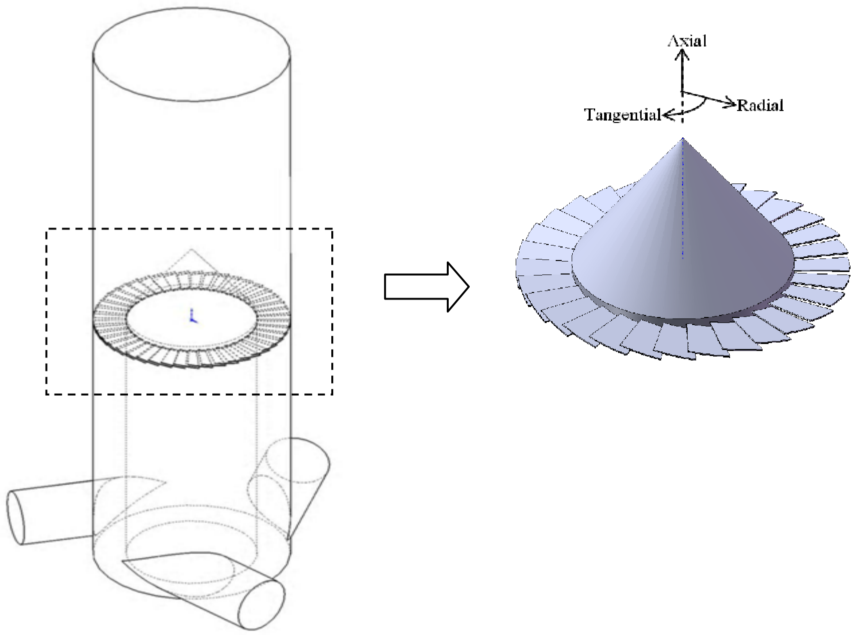


Figure 1.1: Swirling fluidized bed with a conical centre body

The purpose of this study is to gain fundamental understanding on the aerodynamic characteristics inside a Swirling Fluidized Bed (SFB) that will optimize the bed design towards various industrial applications. Although, the publication of the SFB and operating equipment's with a similar principle to the SFB seem commercially available, study deeper influence types of the plenum chamber along with blade distributors are rather scanty.

Hence, this study proposes a full geometry numerical study of the SFB via a Computational Fluid Dynamics (CFD) approach. Commercial CFD package GAMBIT 2.4.6 and FLUENT 6.3.26 in UTHM has been held to investigate the velocity distribution and pressure drop influence the type of plenum chamber. Validation from the CFD work has been carried out through laser measurement technique, namely Particle Image Velocimetry (PIV) which is also available in UTHM. The findings will be useful for scale-up and erection of actual gas-solid contacting systems such as dryers and combustors which use the swirling flow principles.

1.1 Background of Study

A SFB consists of an annular distributor along with the number of blades arrangements at an angle to the horizontal inclination were injected of gas through the distributor. Influence of various types of the plenum chamber the SFB gives better fluidization compare to conventional fluidized bed. SFB has several advantages such as a good quality fluidization through distributor and having a low distributor pressure drop. Though a number of beds are widely used in many applications operations such as the rotating bed, vortexing bed and swirling bed, only limited study has been reported. Therefore, a detailed aerodynamics study on the SFB has been highlighted to address some of the limitations of the SFB.

1.2 Problem Statement

The swirling fluidized bed is an outcome of studies carried out in order to overcome disadvantages of the conventional fluidized bed (Sreenivasan and Raghavan, 2002; Ozbey and Soylemez, 2005; Safiah *et al.*, 2008; Shu *et al.*, 2007). Although equipments operating with swirling principles are available commercially, the fundamental aspects regarding air flow distribution inside the bed, particularly the effect of various distributor configurations has never been published as far as author’s knowledge. A number of parameter affects the air flow distribution inside the SFB; namely number of blades, blade inclination which directs the flow at certain angle, annular width, type and geometry of the centre body and bed aspect ratio such as diameter, height and etc. It’ll be a fruitful endeavour to investigate these parameters and the effect of the SFB’s aerodynamic characteristics. Due to the highly complex nature of flow, numerical study via commercial CFD package has been applied in this study. Experimental study using PIV has been carried out for validation of the CFD simulations as well as flow visualization.

1.3 Objective

The investigation via CFD and PIV of aerodynamics characteristic in the plenum chamber with tangential entry of the SFB through to blade distributor along with a various horizontal inclination is more complex and different from the previous study.

Herewith, no work has been done and publishes especially on this case. The objective of this study is to identify the characteristic of air flow distribution with a various blade distributor configuration and the type of tangential entry plenum chamber in a Swirling Fluidized Bed (SFB).

1.4 Scope of Study

The investigation involves an extracting data from numerical simulations and validated with experimental results. For the numerical investigation part, the commercial CFD package code FLUENT 6.3.26 has been used to analyze the characteristic of flow distributions in a Swirling Fluidized Bed (SFB) through various distributor configurations with tangential entry plenum chamber. While the experimental set-up has been carried out to validate the numerical simulation data by using a Particle Image Velocimetry (PIV).

This study will focus on the following below:

i. Development of computation domain via solid modeling
ii. A full geometry of SFB involving with variation of:
   a. Number of blades (60 blades)
   b. Tangential entry of air with single, double and triple inlet
   c. Inlet velocity up to 2.25 m/s (0.02057 kg/s mass flow rate)
   d. Variation of blade horizontal inclination angle (12° and 15°)
iii. Grid sensitivity analysis
iv. Investigation of flow distribution and pressure drop for all cases.
v. Validation with 3-D PIV system (Dantec Dynamic)

1.5 Significant of Study

The significance of this study is to identify the characteristic of flow distributions in a SFB for various distributor configuration and bed geometry. The findings will provide a better understanding of the nature of flow distribution in a SFB. An optimum design of SFB will tends a low pressure drop and produces a uniform velocity through the distributor configuration. At the end of this research it's expected that this distributor configuration study might lead an optimum performance of SFB for the purposed work in utilization of biomass in worldwide industry.

CHAPTER II

LITERATURE REVIEW

2.1 Fluidization

Fluidization is an operation by which fine solids are transformed into a fluid like state through contact with a gas or liquid (Nag, 2008). This technology was known contacting method which has been used in processing industry such as reforming of hydrocarbons, coal carbonization and etc. It's also well recognized in nuclear engineering. The fluidization operation requires a containing vessel with a porous base which the fluid can be introduced to the bed. The porous base will distribute the fluids across the base of the bed uniformly (Howard, 1989). Porous base in the technology fluidized bed also known as a distributor. The bed will expands when imposed of upward flow rate then the bed can become higher from its initial (Howard, 1989).

2.2 Swirling Fluidized Bed (SFB)

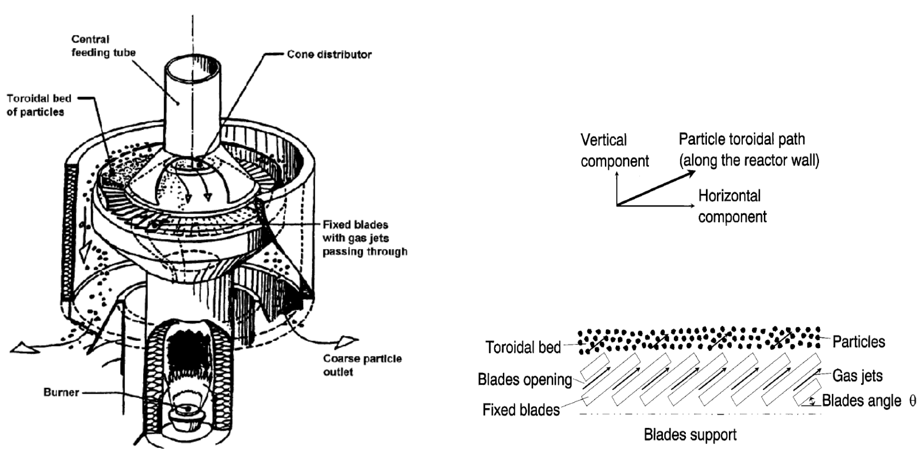
One of the recent developments in providing a variant in fluidized bed operation is the swirling fluidized bed (Wellwood, 1997). The swirling fluidized bed is a relatively new development. In contrast with conventional fluidization, in swirling fluidized beds the fluidizing medium enters the bed at an inclination to the horizontal. Directed thus by a suitable design of a distributor has been purposed by Wellwood (1997). The previous study by Kamil *et al.* (2007) shown swirling motion imparts special characteristics to the bed, which are considerably different from that of conventional fluidized beds.

2.3 Related Works

This topic presents a variant literature review on the conventional fluidized bed, which are relevant to the scope of this study. A good understanding of the swirling fluidized bed technology behavior such as parameters of hub geometries, various distributor configuration and type of plenum chamber was performed. Some related works to the current study are reviewed and reported as below:

2.3.1 Toroidal Fluidized Bed (Torbed)

Shu *et al.* (2000) reported among the most successful in fluidized bed reactor was the Torbed reactor. The Torbed reactor has been involing with the mass and heat transfer processing and it become the new thermal processing technology. This technology has been used successfully in many applications such as combustion, drying, gas scrubbing, calcination and mineral processing. The reactor has a gas distributor consisting of angled blades in an annular form at the reactor bottom, as shown schematically in Figure 2.1 (a).



(a) (b)

Figure 2.1: Toroidal fluidized bed (TFB) Reactor; (a) Configuration of a TFB reactor and (b) Principle of particle movement in a TFB reactor (Shu *et al.*, 2000)

Furthermore, Shu *et al.* (2000) stated, when an air forced pass through openings of the blades, the gas will be following into the blade array then a high velocity jets keep the bed particles in suspension and rotating toroidally such as the principle is illustrated in Figure 2.1 (b). The Torbed reactor was developed based on experience for the effective exfoliation of perlite and vermiculite operated in the coarse particle mode.

This technology is now extended for fine particle processing. In the latter operation, the fine particles should be quickly fluidized and processed in the reactor chamber compare to the former conventional fluidized bed (Shu *et al.*, 2000). Regarding to this technology, the toroidal mixing motion of the particles ensures a high heat and mass transfer rates. As a conclusion, the torbed reactor could effectively process a very fine particle such as Geldart particle B, C, and D but large Geldart particle A was pointed out of the coarse portion due to kinematic limitations. Therefore, this study has been measured the air flow distribution in a Swirling Fluidized Bed (SFB) same as the driving force of particles to move over the upon entering blade spacing in Torbed reactor.

2.3.2 Annular Spiral Distributor

The concept of the annular distributor has been introduced from spiral distributor that proposed by Ouyang and Levenspiel (1986) as shown in Figure 2.2. The work of Sreenivasan and Raghavan (2002) in the hydrodynamic characteristics of a swirling fluidized bed which was studied experimentally as well as an analytical model is a pioneering to Kaewklum and Kuprianov (2010) studied.

The same principle from Shu *et al.* (2000) that inclined injection of gas into fluidized bed of particles by using an annular distributor blade it will produce a tangential motion along the region the swirling action of the bed overcomes certain particular shortcomings of the conventional shallow bed through at the swirling zone; no no bubbles are seen and no gas by passing occurs. Sreenivasan and Raghavan (2002) stated that the annular distributor would reduce the radial variaton in the centrifugal force compared to the circular distributor. However, in order to derive maximum advantage of the swirl motion of particles, the bed appears more suited for operation in the shallow mode.

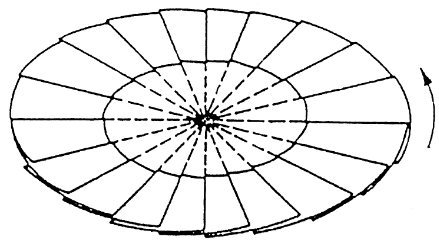
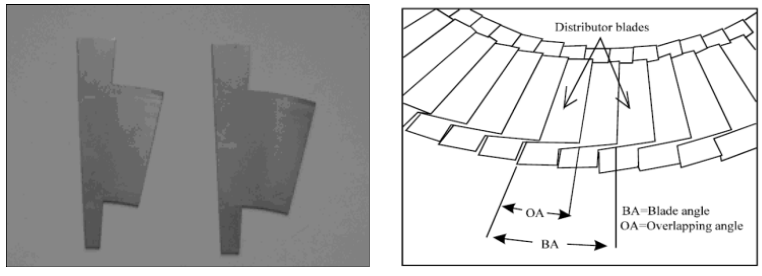


Figure 2.2: The annular spiral distributor and the air flow is in the counterclockwise direction (Ouyang and Levenspiel, 1986)

Due to a helical path, the gas has a slightly longer travel than the bed height and particle circulation does not depend on the bubbles. Therefore the feed, at one point of the swirling bed, it disperses quickly and thoroughly in the bed (Sreenivasan and Raghavan, 2002). However, influences of the fluid density are most significant followed by the blade angle and superficial gas velocity (Kamil *et al.*, 2007).

The similar study has been done by Batcha and Raghavan (2011) were focusing on a various blade distributor configuration. In spite of the potentials for vast industrial applications of the swirling fluidized bed, there are very few systematic studies of such a bed, though the principle has already been used in commercial equipment. As the stable mixing regime in the absence of bubbles and hence, of gas passing through slugging, swirl bed has a bright future in solid-gas processing. From this study, Batcha and Raghavan (2011) discovered that pressure drop of the bed increased with superficial velocity after minimum fluidization, in contrast to conventional fluidized bed. It was also found that the blade geometry has less effect on bed performance, compared to fraction of open area and particle size as shown in Figure 2.3.



(a) (b)

Figure 2.3: Configuration of blade SFB; (a) Blades used to form annular and (b) Blade angle and blade overlapping (Batcha and Raghavan, 2011)

Kamil *et al.* (2007) studied an analysis of the relative importance of the operating parameters on the hydrodynamic characteristics of swirling fluidized beds, and he reported that two-dimensional (2D) analytical model, investigating on the influence of blade angle, gas and particle's density from their parametric analysis has been revealed that gas and particles density has the most influential parameters followed by the blade angle from their parametric analysis. The comparison of experimental from the previous study is shown in Table 2.1. The initial concept of an annular distributor has been purposed by Ouyang and Levenspiel (1986). Based on this new concept many researchers have shown their interested to study more depth through different parametric study.

Table 2.1: Experimental details for the comparison of type of plenum chamber

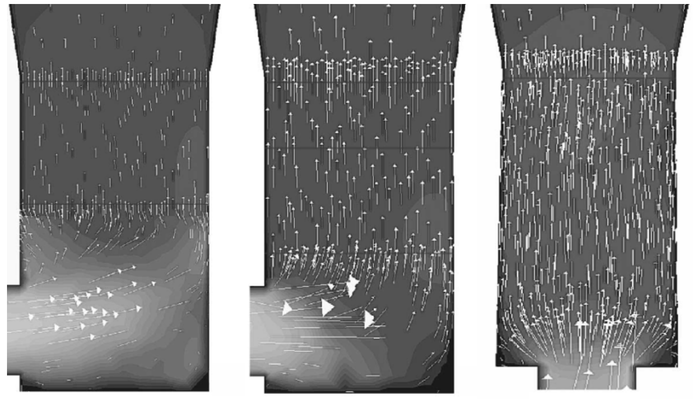
Researchers	**Type of Plenum Chamber**	**Number of Blade Distributor**	**Angle of Inclination of Blade**
Ouyang F. and Levenspiel O. (1986)	-	24 & 32	*Not Stated*
Wellwood (2000)	Tangential Entry	*Not Stated*	10°, 20° & 30° (Horizontal)
J. Shu *et al.* (2000)	Axial Entry	*Not Stated*	25° (Horizontal)
Sreenivasan B. and Raghavan V.R (2000)	Tangential Entry	60	12° (Horizontal)
Keawklum R. et al. (2009)	Axial Entry & Tangential Entry	11	14°
Kaewklum R. and Kuprianov V.I. (2009)	Axial Entry	11	14°
Chakritthakul S. *et al.* (2011)	Axial Entry	22	14°
Batcha M.F.M. and Raghavan V.R. (2011)	Tangential Entry	30 & 60	9° & 12° (Radial)
K.V. Vinod *et al.* (2011)	Tangential Entry	60	15° (Horizontal)
Sheng T.C. *et al.* (2012)	Radial Entry	60	10° (Horizontal)
K.V. Vinod *et al.* (2012)	Tangential Entry	60	9° (Radial) with 10° (Horizontal)
Arromdee P. and Kuprianov V.I. (2012)	Axial Entry	11	14°

As a conclusion, this study has chosen 60 blades with various blade angles of 12° and 15° horizontal inclination same as pilot scale of previous study from Batcha M.F.M. and Raghavan V.R. (2011) and K.V. Vinod *et al.* (2011). From here, the aerodynamic characteristic of a Swirling Fludized Bed (SFB) should be known whether applying an overlapping blade angle will increase a high of tangential velocity and will decrease a lower blade distributor pressure drop.

2.4 CFD Analysis of Air Distribution in a Fluidized Bed

A number of researchers have studied air distribution in fluidized bed system. Depypere *et al.* (2004) stated that the primary factor influencing fluidized bed processing is the airflow and its distribution. In order to understand the fluidization hydrodynamics of a specific fluid bed operation, it is essential to assess how airflow is distributed through the equipment. Numerical modeling techniques such as CFD offer a powerful tool to simulate fluid flow and heat transfer problems. Hereby, the mass conservation or continuity equation, the momentum conservation or Navier–Stokes transport equations and the energy conservation equation are numerically solved using commercial CFD package, FLUENT.

Depypere *et al.* (2004) reported that main outstanding difficulty for numerical modeling techniques still remains the simulation of the effects of fluid turbulence. In order to approximate the turbulence scales, the solution variables are decomposed into their mean and fluctuating components and the Reynolds Averaged Navier–Stokes (RANS) equations are obtained. The modified equations however contain additional unknowns that need to be determined using turbulence models in order to achieve closure. Based on a few equation turbulence models, the standard k-ε model has been selected and be applied into his numerical study. Figure 2.4 shows an example of CFD simulation results in the plenum chamber. The results are shown for the pre-distributor, the ceramic balls packing and the central bottom plenum air inlet modification, respectively.



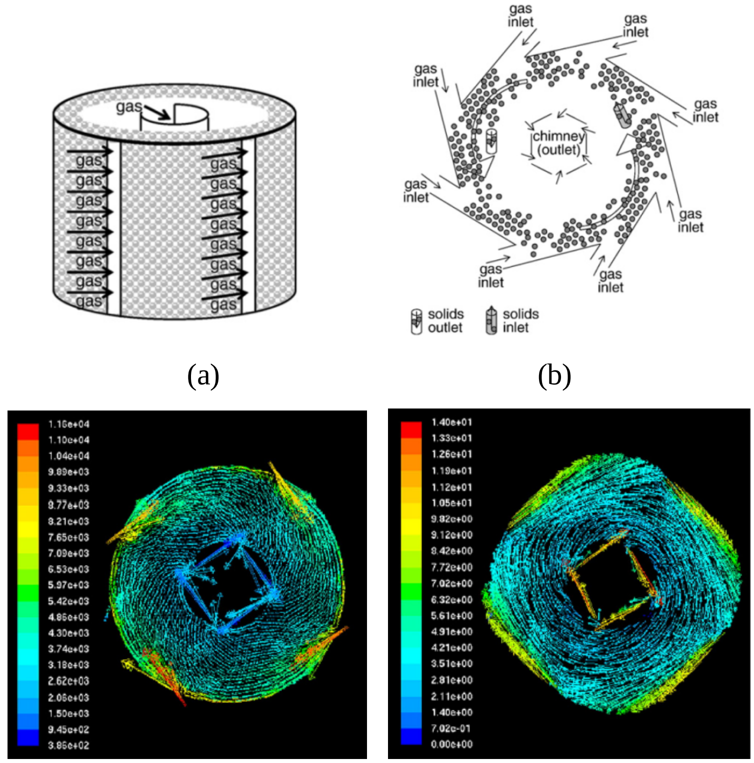
(a) (b) (c)

Figure.2.4:. CFD simulated airflow for a modified plenum chamber design cases; (a) Pre-distributor, (b) Ceramic balls packing and (c) Bottom plenum air inlet (Depypere *et al.*, 2004)

As a conclusion, this study has been used a commercial CFD package FLUENT to predict the air flow distribution in a Swirling Fluidized Bed (SFB) same as Depypere *et al.* (2004) are being used in his study. Depypere *et al.*(2004) has been study using a distributor more likely to conventional fluidized bed. Therefore, based on his study it will guide how to simulate of 3-D Swirling Fluidized Bed (SFB) geometry.

2.4.1 Static Bed with 4 Gas Inlet and 4 Chimney Outlets

Wilde and Broqueville (2008) have introduced a rotating fluidized beds in a static geometry based on the new concept of injecting the fluidization gas tangentially in the fluidization chamber, via multiple gas inlet slots in its cylindrical outer wall. The tangential injection of the fluidization gas fluidizes the particles tangentially and induces a rotating motion, generating a centrifugal field. The concept of a rotating fluidized bed in a static geometry and the schematic representation of the 2-Phase CFD simulation of a rotating fluidized bed in a static geometry with 4 gas inlets, 4 chimney outlets, and a side solids inlet as shown in Figure 2.5.



(a) (b)

(c) (d)

Figure 2.5: The concept of a rotating fluidized bed in a static geometry; (a) View an inlet gas to chamber, (b) Static geometry rotated fluidized bed (c) Gas phase velocity vectors colored by the relative pressure (d) Solids velocity vectors colored by the solids velocity magnitude (Wilde, 2008)

As reported by Wilde and Broqueville (2008), a radial fluidization of the particle bed is created by introducing a radially inwards motion of the fluidization gas, towards a centrally positioned chimney. Precisely balancing the centrifugal force and the radial gas–solid drag force requires an optimization of the fluidization chamber design for each given type of particles. Solids feeding and removal can be continuous, via one of the final plates of the fluidization chamber. Provided that the solids loading is sufficiently high, a stable rotating fluidized bed in a static geometry is obtained. This requires to minimize the solids losses via the chimney. With the polymer particles, a dense and uniform bed is observed, whereas with the salt particles a less dense and less uniform bubbling bed is observed. Solids losses via the chimney are much more pronounced with the salt than with the polymer particles. Slugging and channelling occur at too low solids loadings.

Besides, Wilde and Broqueville (2008) claimed that hydrostatic gas phase pressure profiles along the outer cylindrical wall of the fluidization chamber is a good indicator of the particle bed uniformity and of channeling and slugging. The fluidization gas flow rate has only a minor effect on the occurrence of channeling and slugging: the solids loading in the fluidization chamber being the determining factor for obtaining a stable and uniform rotating fluidized bed in a static geometry.

Wilde and Broqueville (2008) involved a multiple gas tangentially in the fluidization chamber in their study. Compared to this study, Wilde and Broqueville (2008) have injected the fluidization gas via multiple gas inlet slots in the outer cylindrical wall of the fluidization chamber and their claimed that by forcing the fluidization gas to leave via the top-end plate of the fluidization chamber is not a true rotating fluidized bed. Therefore, this study wants to investigate the characteristics of air flow distribution which are involved various velocity profiles that can lead more sustainability to the bed in a Swirling Fluidized Bed (SFB).

2.4.2 Static Bed with Radial Chimney

Dutta *et al.* (2009) have provided a schematic conceptual representation of the rotating fluidized bed in static geometry (RFB-SG) is shown in Figure 2.6. The figure represents a cylindrical vessel, named fluidization chamber, with tangential openings (shown with arrows marked as INLET) positioned along the periphery of the cylinder.

Although, Dutta *et al.* (2009) stated that the rotating fluidized bed is meant to be operated in either axis of rotation, the simulations presented in this study are based on a vertical position of the bed. The fluidization gas is forced to leave the fluidization chamber via a central chimney, introducing a radial motion of the gas. The tangential gas velocity component will fluidized the particle bed and the produce a centrifugal force. The radial gas velocity component induces a radial drag force causing radial fluidization of the particle bed. Both component velocities will generate turbulence.

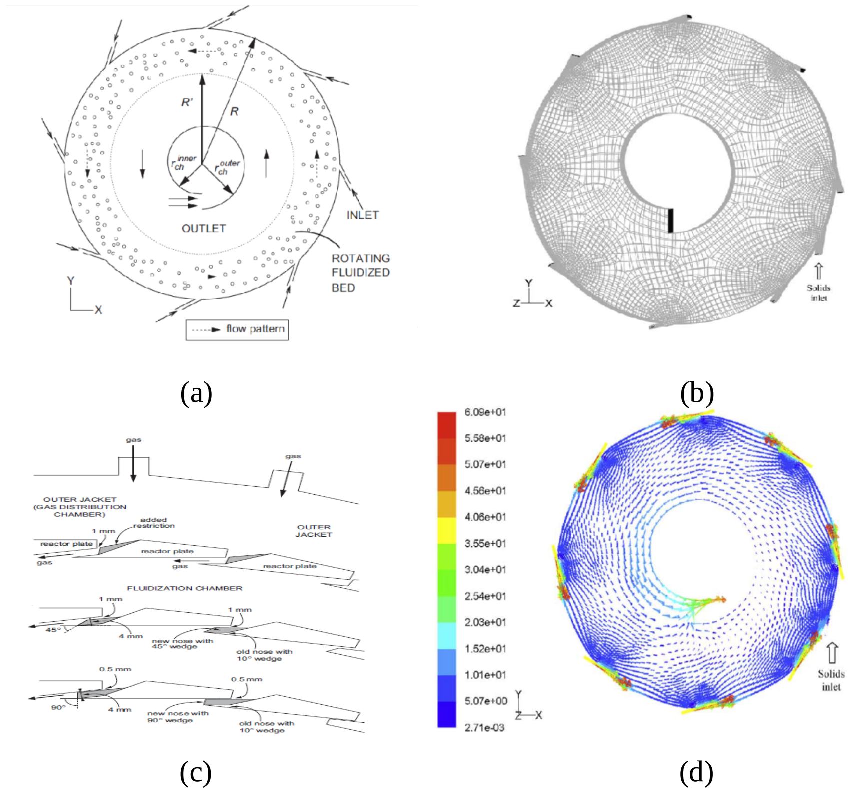


Figure 2.6: Static Bed with Radial Chimney; (a) A schematic 2D representation of the rotating fluidized bed in a static geometry (RFB-SG), (b) Perspective view of the set-up indicating 8 gas inlets (solids inlet and chimney outlet), (c) Schematic representation of gas and solid injector modification and (d) Vectors of gas velocity (m/s) showing stagnation zones downstream of the chimney outlet (Dutta *et al.*, 2009)

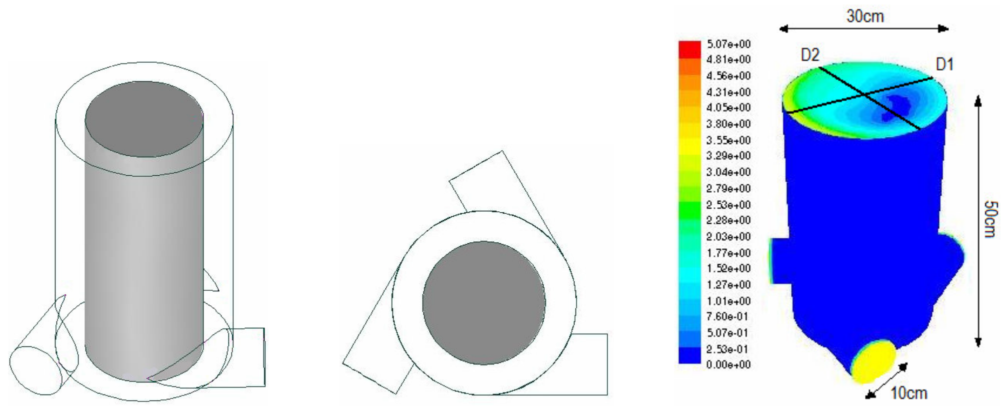
According to Dutta *et al.* (2009) the simulation in this study indicated that the motion inside the particle bed is mainly tangential due to the tangential gas injection, but radial fluidization is also of importance. The latter is determined by the ratio of the centrifugal force and the radial gas–solid drag force. The tangential slip velocity, *v* slip, *t* is calculated to be much smaller than the radial slip velocity, *v* slip, *r*. This large radial slip is expected to be the main contributor in the improvement of inter-phase heat and mass transfer. The gas flow pattern is found to be strongly influenced by the presence of the particle bed.

Dutta *et al.* (2008) found that, at the fluidization chamber design, the increase in radial gas-solid drag force is roughly proportional to a linear or quadratic increase in the gas tangential velocity, while the increase in centrifugal force is roughly dependent to the square of the gas tangential velocity, thereby causing an increase in the gas flow rate. Within the operating range investigated in this study, an interesting feature observed with the modified designs is the decrease in solids loses with an increase in the gas flow rate. Restrictions in the gas inlet slots are shown to be useful to create a pressure drop over the inlet slots sufficiently high, compared to the solids centrifugal pressure. The gas inlet velocity is not influenced by this high pressure drop, as such the non-uniform bed behavior like slugging and channeling which is caused due to local gas velocity variations are avoided.

Alike as the previous study (Wilde and Broqueville, 2008), Dutta *et al.* (2008) have been studied the same geometry by using CFD simulations of the hydrodynamics behavior of rotating fluidized bed in static geometry. The two major velocity profile, namely: tangential velocity and radial velocity that have been indicated from Dutta *et al.* (2008) also been investigated in this study.

2.4.3 Plenum Chamber and Hub Geometries

Safiah *et al.* (2008) studied an analysis of the numerical of the complex flow dynamics in the three-inlet plenum chamber in SFB. This section plays a vital role in distributing the fluid before it enters the distributor. The flow in the plenum of the swirling fluidized bed is different and more complex than the situations studied earlier. The researchers has focused on the influence of the different geometries of flow modifying centre-bodies in the plenum on the flow uniformity and plenum pressure drop as to arrive at an optimum choice of the hub. From this study Safiah *et al.* (2008) found that the three tangential inlets into the chamber an exist as a full length cylindrical hub in the centre of the three-inlet plenum as shown in Figure 2.7 which yields good uniformity in the velocity profile at the distributor along the radial and tangential direction as well as low total pressure drop.



(a) (b) (c)

Figure 2.7: Three-inlets chamber with a full-length cylindrical hub at the center; (a) Isometric view, (b) Top view and (c)Velocity distribution (Safiah *et al.*, 2008)

2.5 Particle Image Velocimetry (PIV) Analysis of Air Distribution

A Particle Image Velocimetry (PIV) system consists of several sub system, in most application tracer particles have to be added to the flow. These particles have to be illuminated in a plane of the flow at least twice within a short time interval (Raffel *et al.*, 1965). The light scattered by the particles has to be recorded either on a single frame or on a sequence of frames. The displacement of the particle images between the light pulses has to be determined through evaluation of the PIV recordings. In order to be able to handle the great amount of data which can be collected by employing the PIV technique, sophisticated post-preprocessing is required (Raffel *et al.*, 1965).

In Figure 2.8 a typical set-up of PIV recording in a wind tunnel is show a small tracer particles were added into the flow and the flow were illuminated twice by means of laser. The light scattered by the trace particles is recorded via a high quality lens. After a development photo-graphical PIV recording is digitized by means of a scanner, the output of the digital sensor is directly transferred to the memory of a computer (Raffel *et al.*, 1965).

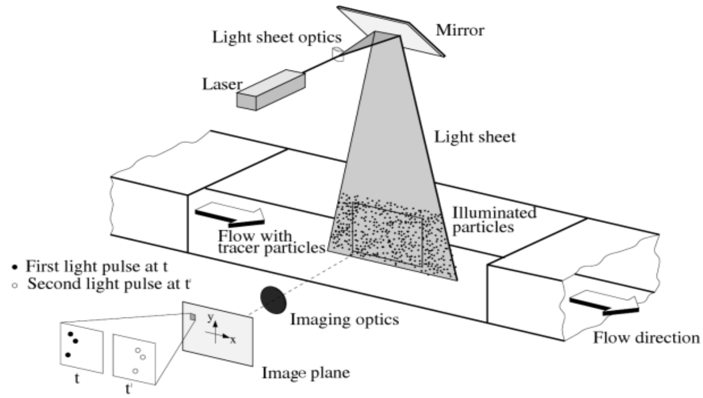


Figure 2.8: Experimental arrangement for particle image velocimetry (PIV) in a wind tunnel (Raffel *et al*., 1965)

2.5.1 Stereoscopic PIV

Stereoscopic PIV uses two cameras to view a flow field from two perspectives so that the out of the plane velocity component can be measured (Raffel *et al.*, 1998). The two components of velocity are nominally perpendicular to the camera optical axis, which are measured from each camera viewpoint. The pair of 2D velocity vectors for a point in the flow is then combined to yield a three dimensional velocity vector (Raffel *et al.*, 1998). Among several optical arrangements of the two cameras, the Scheimpflüg configuration was found to be the best layout as show in Figure 2.9 below:

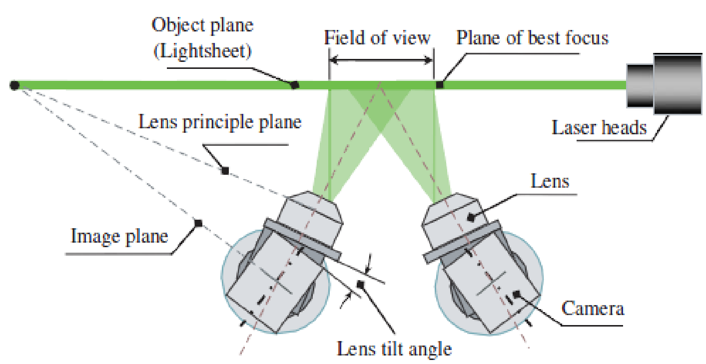


Figure 2.9: Scheimpflüg stereoscopic camera configuration (Raffel *et al.*, 1998)

This technique has been applied in this study. As Raffel *et al.* (1998) reported that by combining the vector fields from the two cameras, the three dimensional velocity fields for the plane in the fluid had been measured.

2.5.1.1 PIV Stereoscopic Camera Arrangement and Calibration

PIV stereoscopic camera arrangement shown in Figure 2.10 corresponds to the set-up described by Peersons *et al.* (2008). The larger the camera elevation angle Ψ, the more accurately W is determined (here: Ψ = 35˚). The camera and lens configuration satisfies the Scheimpflüg condition. A metal foil enclosure surrounds the camera lenses and swirl tube to reduce the level of background illumination, resulting in high-contrast images. The symmetric camera placement ensures identical light scattering characteristics in both cameras (Peersons *et al.*, 2008) A stereoscopic calibration is performed in accordance with Willert (1997). Due to the confined geometry, a single level calibration target is made that fits into the annulus; with two Cartesian dot mark grids on both sides of the target (Peersons *et al.*, 2008).

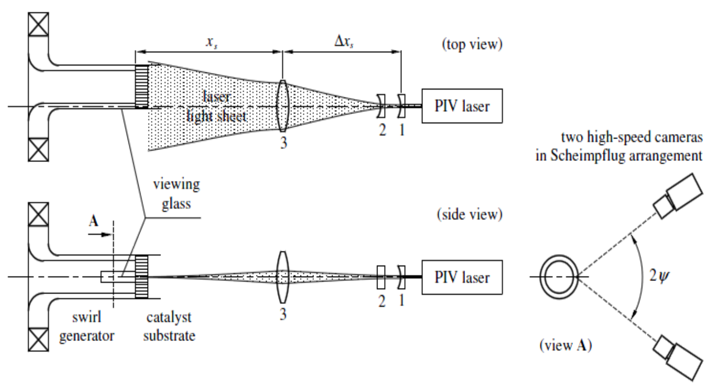
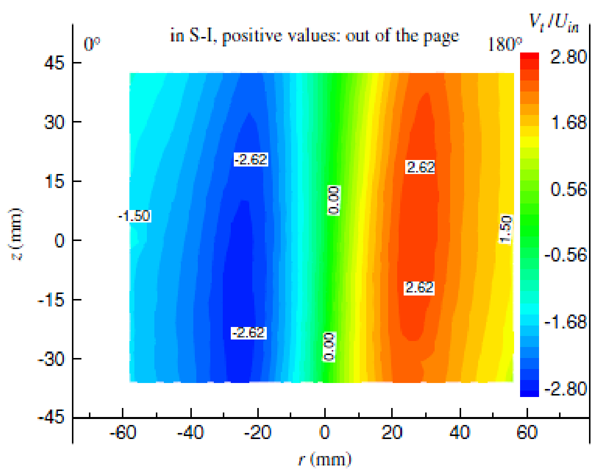


Figure 2.10 : Optical arrangement of laser light sheet and cameras (Peersons *et al.*, 2008)

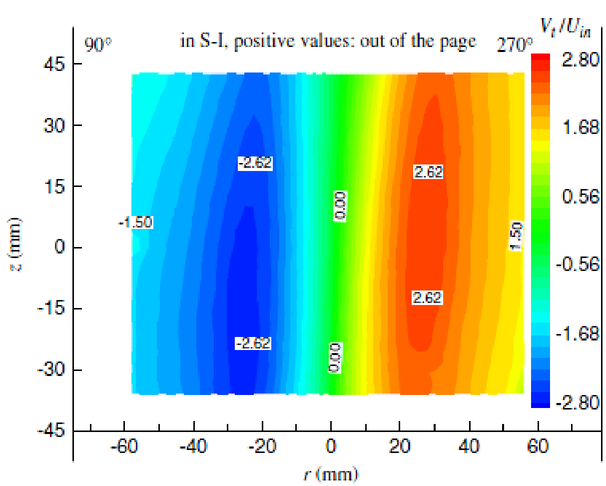
As a conclusion, study by Peersons *et al.* (2008) has been followed for this study, which involved PIV stereoscopic camera arrangement and calibration to get the suitable and best position of the area interrogation at the blade distributor in Swirling Fluidized Bed (SFB).

2.5.1.2 Stereoscopic PIV Studies on the Swirling Flow Structure in a Gas Cyclone

This study is an experiment done to study the swirling flow in a gas cyclone to improve its design (Liu *et al.*, 2006). The three dimensional velocity components of swirling flow are the main focus in this study using a Particle Image Velocimetry with stereoscopic adjustments (Liu *et al.*, 2006). With the common settings of a PIV system, these studies have gained fruitful results as shown in Figure 2.11 below. The Figure 2.11 is shows the distribution of time-averaged tangential velocity in the cylindrical separation space (S-I) which across both 0-180° and 90-270° sections. Based on this study (Liu *et al.*, 2006), the plane contour results at the interrogation area in the Swirling Fluidized Bed (SFB) has been extracted using a Particle Image Velocimetry. Therefore, results this study will validate the plane contour of CFD simulation.



(a)



(b)

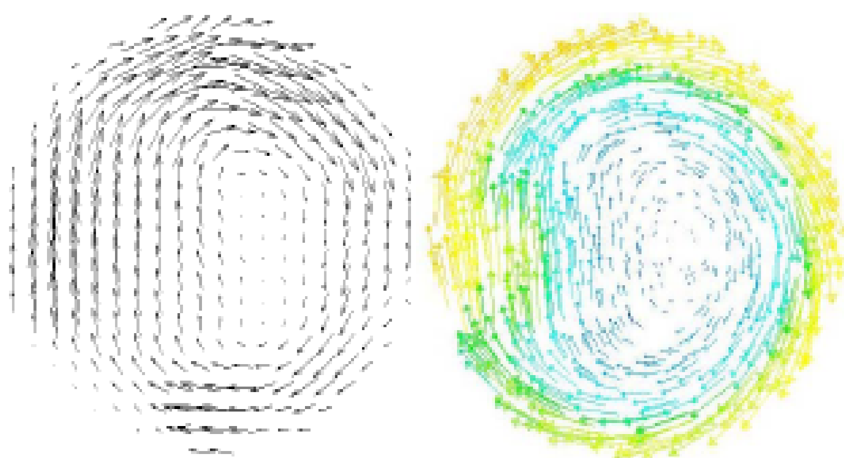
Figure 2.11 : Tangential velocity distribution in the cylindrical separation space across both (a) 0-180˚ and (b) 90-270˚ sections (Liu *et al.*, 2006).

2.5.1.3 Stereoscopic PIV Studies on Plenum Chamber of Swirling Fluidized Bed (SFB)

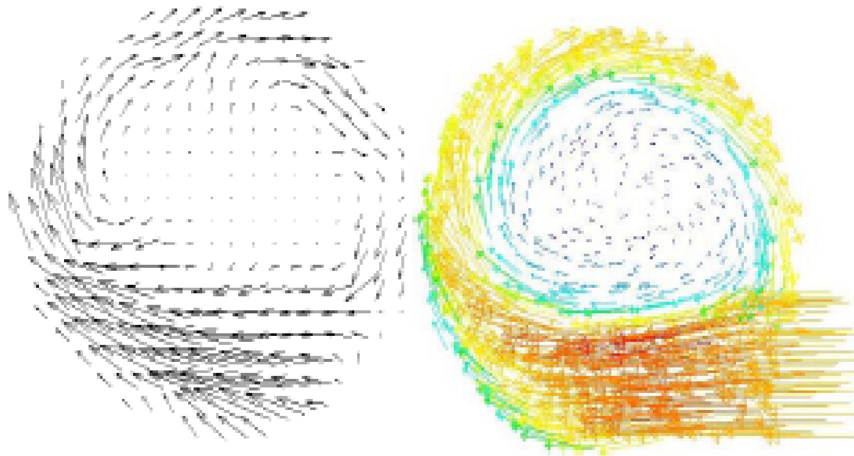
There are very limited of publication that has been conducted to validate numerical simulation result through experimental work data which have be analyzed of a plenum chamber in a swirling fluidized bed. Othman *et al.* (2009) are carried out an experimental and numerical study to investigate the aerodynamics behavior in the plenum chamber in a SFB.

Based on this study, Othman *et al.* (2009) expected to lead an optimum design that will produce an optimum performance characteristic of flow distribution in a SFB. By using a numerical simulation method (CFD) the air flow of plenum chamber has been predicted and being validate with experimental work data (PIV) to find agreement between the two methods of studying of air flow in fluidized bed (Othman *et al.*, 2009).

From this study the results have shown an average of 15.6% discrepancy and it is confirmed that good agreement is obtained (Othman *et al.*, 2009). Figure 2.12 shown the following of the 2-D airflow vectors in the plenum chamber and it's being captured using PIV apparatus and FLUENT simulations (Othman *et al.*, 2009). As a conclusion, the present study has a similar study with Othman *et al.* (2009) and based on his PIV experimental set-up, this study will be easy to follow.



(a) (b)



(a) (b)

Figure 2.12 : Velocity vector on the top plane (above) & bottom plane (bottom); (a) PIV and (b) CFD (Othman *et al.*, 2009).

CHAPTER III

METHODOLOGY

Air flow distribution in a swirling fluidized bed has been investigated using Computational Fluid Dynamics (CFD) software which consists of GAMBIT 2.4.6 & FLUENT 6.3.26 applications. Afterwards, the numerical simulation result has been validated through an experimental work data by using a Particle Image Velocimetry (PIV). The swirling fluidized bed has been modeled in SolidWork due to the user friendly applications. The deviation of the chosen methodology to the experimental data is then determined to arrive at the average discrepancy. The two parameters: namely, the types of tangential entry plenum chamber and the angle inclination of blade distributor have been changed in this study to obtain the correlation between the blades distributor configuration with the air flow distribution in a SFB. The agreement between these methods will validate the numerical method.

3.1 Experimental Set-up

The experimental system has been conducted to verify the numerical approaches which have be uses to investigate the air flow distribution in a SFB. Data from this experimental will provides the least deviation between numerical simulation result and experimental work data afterward a numerical methodology will be selected.

3.1.1 Instrumentations

The airflow rate into double entry plenum chamber has been measured by using a pitot static probe inserted into the pipe as shown in Figure 3.1. It measures a static and stagnation pressure in both locations at tangential entry of pipe. A digital manometer of resolution of 0.1 Pa has been used to measure the pressure differential across the pitot static probe. It has been measured in both static and stagnation pressure on the entry of plenum chamber, thus permits determination of the inlet air flow velocity from Equation 3.1 (Pritchard and Leylegian, 2011). With the fully developed flow at different radial positions inside the pipe, the air velocity can be measured at the centre of axis, v_c.

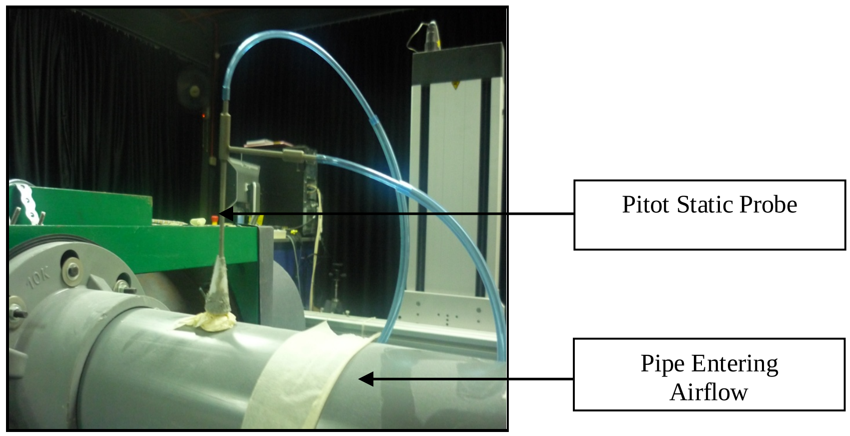


Figure 3.1: Positioning of the pitot static probe inside plenum inlet

Bernoulli's Equation for air reduces to:

$$P_0 - P_2 = \frac{1}{2}\rho v_c^{\ 2} \tag{3.1}$$

$$v_c = (\sqrt{\frac{2(P_0 - P_2)}{\rho}} \qquad \text{(derived from equation 3.1)} \tag{3.2}$$

Static pressure tappings were provided at three (3) planes on the plenum chamber. One (1) plane is 5 cm above the distributor while the others two (2) located at the tangential entry pipe (15 cm away from the column) as shown in Figure 3.1. The purpose for measuring the two (2) points at the tangential entry pipe will be verify the same air flow velocity inlet to plenum chamber. Four tappings were made on the above distributor at the surface of acrylic column as shown in Figure 3.2 and one at the inlet pipe. With the existence of multi tappings it should have an average

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