INFLUENCE OF PLENUM CHAMBER CONFIGURATION ON AIRFLOW AND PRESSURE CHARACTERISTICS IN FLUIDIZATION SYSTEMS VIA COMPUTATIONAL FLUID DYNAMICS ANALYSIS

by

HAZIZUL BIN HUSSEIN
(1931413055)

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LIST OF ABBREVIATIONS

DOE	Design of Experiment
SFB	Swirling Fluidized Bed
TV	Tangential Velocity
AV	Axial Velocity
RV	Radial Velocity
VM	Velocity Magnitude
RMSD	Root Mean Square Deviation
RSM	Reynold Stress Models
RSM	Response Surface Methodology
RANS	Reynolds Averaged Navier Stokes
CFD	Computational Fluid Dynamic

Pengaruh Konfigurasi Ruang Kebuk Terhadap Ciri-Ciri Aliran Udara dan Tekanan Dalam Sistem Pembendaliran dengan Analisis Pengkomputeran Dinamik Bendalir

ABSTRAK

Sistem pembendaliran digunakan secara meluas dalam penjanaan kuasa, proses kimia, industri pemprosesan mineral, proses pengeringan dan lain-lain. Kajian ini dilakukan adalah kerana terdapat sedikit kekangan pada sistem pembendaliran konvensional yang dapat disimpulkan seperti; (i) Beberapa jenis reka bentuk pengedar, dapat mempengaruhi ukuran gelembung dan menurunkan prestasi pembendaliran, (ii) Sistem pembendaliran konvensional tidak menunjukan bendaliran pada satu nilai tertentu yang secara tidak langsung mempengaruhi kelakuan *beds*, dan (iii) Penurunan tekanan dalam pembendaliran konvensional tidak tetap dengan peningkatan halaju udara yang akan mempengaruhi berat *beds* atau kandungan kelembapan *beds.* Oleh yang demikian, kajian semasa bertujuan untuk; (i) Menilai keupayaan jangkauan operasi beberapa jenis ruang kebuk dan ketinggian kon pada pengedar bilah annulus dalam sistem pembendaliran, (ii) Keupayaan untuk mengenalpasti komponen halaju pada pengedaran aliran udara dengan menggunakan rekabentuk ruang kebuk dan ketinggian kon terpilih, (iii) Menilai keupayaan geometri optimum bagi konfigurasi ruang kebuk dan ketinggian kon yang boleh mengatasi kelemahan sistem pembendaliran sediaada. yang memfokuskan kepada penurunan tekanan rendah, halaju seragam dan tinggi halaju tangen. Untuk mencapai tujuan yang digariskan, beberapa kaedah telah dicadangkan dalam kajian ini. Pertama, simulasi penyelakuan Pengkomputeran Dinamik Bendalir (CFD) digunakan untuk menyiasat parameter yang mempengaruhi pengedar kedalaman pengedar bilah anulus yang berbeza-beza iaitu (150 mm, 200 mm, dan 250 mm) dan pelbagai ketinggian kon iaitu (150 mm, 200 mm dan 250 mm). Kedua, CFD digunakan untuk menyelidiki ciri-ciri halaju setiap komponen halaju seperti magnitud halaju, tinggi halaju tangen, halaju paksi dan halaju radial serta penurunan tekanan yang dilakukan oleh konfigurasi pengedar berongga. Dan ketiga, data yang diekstrak telah dinilai dengan menggunakan analisis statistik pada nilai purata, sisihan piawai, dan juga menggunakan kaedah pengoptimuman seperti *Full Factorial Design (FFD).* Penemuan daripada hasil kajian dibuat mendapati parameter yang paling signifikan dan optimum yang mempengaruhi reka bentuk sistem pembendaliran adalah pada ketinggian kon 200 mm dengan kedalaman bilah pengedar anulus 100 mm. Ini adalah kerana analisis terhadap rekabentuk sistem pembendaliran pada kajian ini mempunyai penurunan tekanan yang lebih rendah (6.89 Pa) dan nilai sisihan piawai terhadaap halaju tangensial yang rendah iaitu 3.704%. Selanjutnya, analisis dengan menggunakan kaedah ANOVA telah menunjukkan bahawa kedalaman bilah anulus mempunyai parameter yang signifikan pada nilai-nilai penurunan tekanan. Berdasarkan kaedah pengoptimuman *Full Factorial Design (FFD),* dengan merujuk kepada dua faktor iaitu kedalamn pengedar bilah anulus dan ketinggian kon, penurunan tekanan adalah parameter yang paling signifikan dalam menyumbang kepada penggunaan tenaga yang optimum terhadap sistem pengapungan.

Influence of Plenum Chamber Configuration on Airflow and Pressure Characteristics in Fluidization Systems via Computational Fluid Dynamics Analysis

ABSTRACT

Fluidization systems have the potential to be widely used in the power generation, chemical and mineral processing industries. These studies are carried out due to the constraints on conventional fluidization systems, which infers to (i) Several types of distributor design can influence the bubble size and lower down the fluidization performance, (ii) The conventional fluidization systems does not fluidized at one specific value that directly affect in the bed behavior, and (iii) The pressure drop in conventional fluidization is not constant with increasing air velocity, which affects on bed weight or bed moisture content. Therefore, the current study aims to (i) assess the operational range of several plenum chamber configurations and cone height modelled for annular blade distributor application in fluidization systems, (ii) investigate the velocity component on airflow distribution using a selected plenum chamber configuration and cone height, and (iii) evaluate the optimized geometry of plenum chamber configuration and cone height that could overcome the weaknesses associated with current fluidization systems towards uniform velocity distribution, low tangential velocity and high-pressure drop via statistical analysis. To achieve the goal outlined in this study, several methods have been proposed. First, the numerical simulation of Computational Fluid Dynamics (CFD) is used to investigate the parameters that influence annular plenum chamber depth (0 mm, 100 mm and 200 mm) and various cone heights (150 mm, 200 and 250) through 60 blades number and 15° inclination angle. Second, the CFD is used to investigate the velocity characteristics at each velocity component, such as velocity magnitude, tangential velocity, axial velocity and radial velocity, as well as the pressure drop affected by plenum chamber configuration. This criterion has been evaluated using statistical analysis on the mean value, standard deviation, and Full Factorial Design (FFD) optimization method. The most significant finding in this study representing the optimum design of the SFB system was cone height 200 mm with annular blade distributor depth 100 mm. This is because it has a lower pressure drop (6.89 Pa) and a relatively low standard deviation on the tangential velocity of 3.704%. Furthermore, extended analysis using ANOVA analysis has shown that annular blade distributor depth has a significant parameter on the values of pressure drop. Based on the optimization method of Full Factorial Design (FFD) results, referring to the two factors of annular blade distributor depth and cone height on current fluidization systems, the pressure drop is the most significant parameter that contributed to the less energy consumption on the fluidization systems.

CHAPTER 1 : INTRODUCTION

1.1 Background and Research Motivation

Fluidization is a new technique with advantageous and desirable properties for many industrial applications, including drying, combustion, biomass gasification, oxidation, metal surface treatment, catalytic and thermal cracking, and coatings. Moreover, fluidization is the process by which solid particles are suspended in a fluid-like state while being subjected to several forces. Gravity, buoyancy, and drag are among these forces. This force may be sufficiently strong to destabilize the particle structure in the bed. When the fluid velocity is increased, the fluid drag maintains the total weight of the particles.

The fluidization system is used in many drying processes, for example, in the agricultural sector, such as black pepper, cocoa beans, coffee beans, etc. Since drying rate and thermal efficiency have advantages, a fluid surface has been included in the drying process. High heat and mass transfer rates between the gases and the particles are conceivable due to the large interaction area between the particles and the air. It also ensures that the mixture has a homogeneous blend of solids and uniform moisture distribution in the mix. Due to its rapid drying, this was a cheap drying procedure in comparison to other drying methods. Another possible aspect of functioning is that solids can be added or removed.

However, there are several limitations to the approach. Other examples include limiting the flow of gas to ensure that the fluidized bed does not lose part of its elutriation due to a typical bubbling gas fluidized bed. In addition, limitation for the fluidization, the bed's exact force limit must be maintained. Furthermore, for efficient fluidization, there are constraints on particle size, size distribution, and shape.

Numerous efforts have been directed towards rectifying the issues associated with conventional fluid beds and improving their uniformity. However, developing these kinds of fluidized beds, such as circulating fluidized beds, tapered fluidized beds, centrifugal fluidized beds, spotted fluidized beds, and Swirling Fluidized Beds, created numerous forms of fluidized bed equipment. In addition, more recent designs for fluidized beds have been developed to consider the adverse side effects observed in current fluidized beds.

A recent technology that has recently dealt with the current study is Swirling Fluidized Bed (SFB). The SFB, the other fascinating fluidized beds, use gas distributed at an angle and combined with fluidizing to produce a swirling effect in the fluidization zone. This means that after the gas flow has been separated into vertical and horizontal components, each may then be accountable for creating its swirling motion (Sreenivasan et *al.,* 2002). On the other hand, the SFB has its own limits. While most of SFBs employs an annular distributor (Tawfik et *al.*, 2020a, Tawfik et *al.*, 2020b, Wu et *al.*, 2021a and Wu et *al.*, 2021b), that only has an annular region, which limits the overall size of the distributor.

The present work introduces and studies a component of a gas velocity that would make the continuous fluidized bed that incorporates an annular blade distributor, angular gas injection, and swirling motion of bed material in a circular path, as shown in

Figure. There have several advantages by continues the studies of the annular blade distributor in the SFB system. A swirling bed would function at a higher superficial velocity with less elutriation when injecting gas at an angle. This condition may be the annular blade distributor design, gas injection angle, and vertical flow of gas entering the bed is much smaller in an SFB than a horizontal flow. The distributor's sophisticated design ensures efficient gas distribution without imposing excessive resistance on the flow of gas. In the real industry application, the particles are pushed outwards by centrifugal force. It then pulls them away from the center and toward the outside wall, with lower upward gas velocity (Sreenivasan et *al*., 2002). As the air velocity increases, the swirling in the middle of the bed impairs the passage of particles from the center to the outer wall. As a result, gas bypassing may occur in an empty region that will be created towards the inner wall of the column.

Usually, the flow rate of gas entering the bed can be separated into three components: axial, radial, and tangential. These three velocity components could be described as axial velocity produces fluidization while tangential velocity offers a swirling effect in industrial applications. Due to the swirl, gas is experiencing centrifugal force, which is the source of the radial velocity. Figure 1.1 shows the normal configuration of the SFB. Here, the gas is injected horizontally into the bed at a certain angle of the blade. The velocity of the gas would be measured in the vertical dimension of v sin ϴ at and in the horizontal component v cos ϴ . The vertical component causes liquidation, which causes the horizontal component to swirl (Paulose, 2006). Swirling Fluidized Beds offer different advantages over conventional fluidized beds. There are no bubbles and no gas bypass in the swirling field. Previous researchers (Batcha and

Raghavan, 2011) have conducted experiments in SFB, and the study's findings show that radial distance increases the velocity of swirling particles.

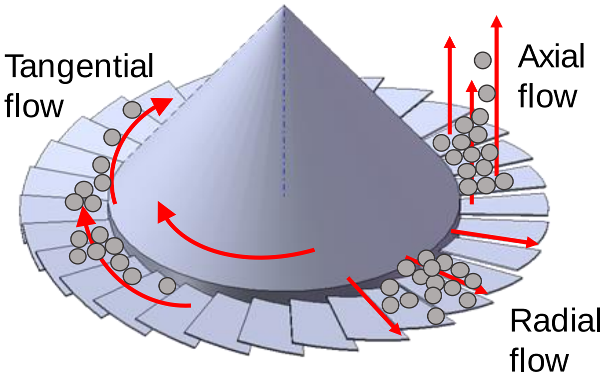

Figure 1.1 Annular Blade Distributor of Swirling Fluidized Bed

While using the annular blade distributor, there is a pressure drop restriction like in the SFB system. Paulose (2006) examined SFB from different distributors and concluded that the pressure drop of the distributor is the lowest for the design of the annular blade distributor. In addition, the pressure drop in the distributors decreases with an increase in the blade angle. The pressure drop in the distributor is also smaller than the past-fluidized beds. An additional advantage is that the size of the system would be minimized. More comprehensive processing is possible due to improving the preservation of the particles and temperature. Big particles difficult to fluidized (Goldart D type) in a conventional bed would be effectively fluidized in Swirling Fluidized Beds.

The analysis will be carried out using a computer simulation using the ANSYS Fluent software program. The problem will be investigated further by modifying the annular blade distributor in order to determine the high tangential velocity and contribute to adequate airflow distribution. Computer modeling will entail the comparison of three velocity and pressure drop components to predetermined parameters.

1.2 Problem Statements

Conventional fluidized bed, with increasing gas velocity, several distinct flow patterns/regimes have been observed (i.e., fixed bed, particle fluidization, bubbling, slugging, turbulent fluidization, etc.). By referring to the distributor design, issues on the bubble production, and eruption in bubbling fluidization, it is difficult to define the gas flow. Moreover, the size of the bubbles can affect the performance of the fluidization. If huge bubbles occur, gas-solid contact will reduce. Numerous design parameters, such as distributor design, can affect the bubble size and fluidization performance. In addition, this swirl of fluid particles formed as a result of the distributor design. When the gas progresses deeper into the bed, it loses its horizontal momentum. Additionally, after a certain point, it simply ceases to exist above the distributor. Therefore, for the bed to move in a circular motion, it must be shallow enough. A great deal of further investigation is still needed to understand what really happened to the airflow behavior in fluidization systems that can propose an intense mixing by setting different annular blade distributor depths in the plenum chamber.

One such approach involves Swirling Fluidized Bed when the horizontal momentum of the air jet is sufficiently decreased as the air jet penetrates deeper into the bed and eventually end at a certain height above the distributor. In this case, the bed is vortexing like one mass. As a result, the particles are swirled strongly, and shearing occurs between the particles and the air. As a result, all transport processes have been strengthened. Compared to the conventional fluidized bed with multiples operating regimens, a Swirling Fluidized Bed is present. For deep beds, there is a two-layer fluidization system with a lower and an upper swirling layer. A striking feature of the swirling bed is that the decrease in bed pressure in the swirling mode increases with the speed of the air (Josephkunju, 2008). However, there are also drawbacks to the Swirling Fluidized Bed. Only the outer annular space can be used in a Swirling Fluidized Bed due to vortex formation accompanied by swirl motion. This resulted in a decrease in the usable area of the blade distributor.

The tangential velocity needed for start swirl motion increases with the weight of the bed. At higher air velocity levels, a portion of the air may be passed through the inside of the distributor. Swirling Fluidized Bed with an annular blade distributor is a modern idea that makes it possible to increase the usable area of the distributor, which forms a trapezoidal shape. In this case, the pressure drop for the distributor was found to be comparatively lower for the slits on the outside of the distributor than the slits opening onto the internal periphery. Research on the effect of particle size and density on the hydrodynamics of conventional fluidized beds has been conducted. However, to this date, only very few studies have been carried out in a fluidized bed field, especially on the configuration of blade design via numerical study. The explanation above was referred to the objective (i).

Due to various swirling flow motions, there are challenges with applying an annular blade distributor in the fluidized bed system. Due to the restriction in its size, only an annular zone of the distributor is utilized in a fluidized bed in swirling motion. The important impact on the minimum fluidization velocity and swirl velocity is the angle of the air jet. There is the potential for some air to bypass the inner part of the blade distributor if it has high velocity. In order to address the drawbacks of annular blade application, a carefully engineered airflow distribution motion is necessary. There is the potential for some of the air to bypass the inner region of the distributor if it has high velocity. Usually, the previous researcher only discussed the mixing of airflows that occurred due to the high tangential velocity component. Besides, some researcher involved with annular blade distributor has little knowledge on the characteristic of airflow during mixing. Due to these limitations, the current study used CFD simulation as its method analysis. The explanation above was referred to the objective (ii).

The conventional fluidization, where the distributor is in perforated plate type, will affect the flow pattern and the mixing in the plenum chamber. As a result of this factor, the current study was more interested in investigating the current airflow behavior by using the annular blade distributor than the conventional distributor fluidized bed. For example, Wormsbecker et *al.* (2007) studied the conventional distributor (perforated plate, wire mesh, and punched plate). They reported that punched plate consists of hooded openings that form rings in a circular pattern. The punched plate distributor formed is proposed to generate a swirling effect in the bed. This type of distributor (punch plate) is shown to admit a superior fluidization performance. However, the pressure drop was too high and not suitable for low-cost operations.

Another related study was proposed by Batcha and Raghavan (2011) on the new type of distributor that mimicked blades turbine with blade inclination angle (9° and 12°) and blade inclination length (15° and 18°) at each blade's distributor. At blade inclination lengths, the higher distributor pressure drops occurred due to greater inclination lengths. This is because it constrains the airflow much longer between the blades before flowing smoothly to the beds. This condition can also be defined as airflows facing the impingement wall (high resistance) before the air passes through the gap between the blade's distributor. So, naturally, the higher number of inlets has a higher pressure drop due to increased airflow rate.

Interestingly, there was only a small variation in the pressure drop for different plenum chambers. This shows the strong dependence of the pressure drop on the air flowrate on its own, while the depth of the plenum chamber has a negligible effect. Reducing the bed pressure is crucial for determining the power required in industrial processes involving gas-solid contact. This airflow characteristic, assessed by statistical analysis, may reveal how much variance in a dependent variable would affect the independent variable. The explanation above was referred to the objective (iii).

1.3 Research Questions

In this study, some research questions were addressed according to the problem statements stated:

i. What is the most significant configuration that influences minimum velocity fluidization and velocity uniformity in the fluidization system?

ii. How much the sufficient of the current fluidization design in terms of high-velocity retention as compared to the different types of plenum chamber?

iii. What are the optimal parameters settings to propose low-pressure drop and high airflow distribution at different types of plenum chambers in the current fluidization systems?

1.4 Research Objectives

The main objectives of these studies are:

i. The ability to assess the operational range of several plenum chamber configurations and cone height modeled for annular blade distributor application in fluidization systems.

ii. The ability to investigate the velocity component on airflow distribution using a selected plenum chamber configuration and cone height.

iii. The ability to evaluate the optimized geometry of plenum chamber configuration and cone height to overcome the weaknesses associated with current fluidization systems towards uniform velocity distribution, low tangential velocity, and high-pressure drop via statistical analysis.

1.5 Research Scope

In order to achieve the objectives outlined in section 1.5, the scopes of this research are as follows.

i. The GAMBIT, Fluent, and Ansys Fluent software were used to conduct a simulation analysis of the current fluidization system design, including airflow distribution and pressure drop studies. The investigation is constrained by physical constraints in $R_S/D_E \leq 1.5$.

ii. The current fluidization systems' simulation performance can only be rated through velocity component formation (tangential velocity) and the pressure drop.

iii. The fluidization system was modeled on a laboratory scale to verify the different types of plenum chamber and cone height performance based on prior results.

iv. The evaluation of numerical simulation of the current fluidization system is limited and constrained to $R_S/D_E \leq 1.5$ and only focusing on uniform airflow distribution.

1.6 Research Significance

This study can clarify and understand the characteristic of flow distribution influence of different types of plenum chamber design and cone height in a fluidization system. This study aims to improve airflow distribution and pressure drop in fluidization systems to obtain the best swirl motion in terms of the velocity component of tangential velocity. With suitable fluid drag where the airflow flows through the annular blade distributor, it will produce a uniform velocity profile at the top of the blade distributor area. Several importances of the study obtained are given below.

Development of plenum chamber configuration capable of optimizing swirl flow by initiating the swirling flow at a specific level of the plenum chamber before the airflow reaching the wall of the blade distributor region. Thus, the impingement airflow is always accompanied and forms a bluff body at the bottom of the distribution zone.

This annular blade distributor can maintain the swirl motion even with an increase in the Reynolds number. Therefore, this annular blade distributor can produce swirling airflow distribution to help the exerted drag flow on the bed of particles. With annular blade distributors, it is also sufficient to accomplish a low-pressure drop on fluidization systems compared to the previous distributor, which had a high-pressure drop value.

1.7 Summary

This thesis describes the research work on the design and modeling of fluidization systems, which have been widely used in drying systems. This research includes the variant types of plenum chamber through to the fixed annular blade distributor. On top of that, this investigation involved aerodynamics features through simulation via computational fluid dynamics. The current applications of the proposed system are air, and different modeling studies were used to investigate the characteristics of velocity distribution. Meanwhile, Chapter 2 reviews the fundamental theories, distributor design, and application of fluidization in a conventional fluidized bed before extending them to the current study of fluidization systems. This chapter also discusses the advantages of the proposed blade inclination angle on fluidization systems like SFB compared to the conventional fluidized bed.

Chapter 3 includes the methodology that contains details of the simulation set-up and presents the procedures to perform design modeling and determining the geometry of different blade distributor configurations in the CFD software package. Discussions on the reasons for choosing certain dimensions and operating parameters for the proposed new model are also included. Chapter 4 deals with computational fluid dynamics studies on the current study of fluidization systems influenced by different plenum chamber designs and cone heights. The modeling was carried out in a three-dimensional frame. The airflow behaviors focused on velocity distribution (velocity magnitude, tangential velocity, axial velocity, and radial velocity), and the pressure drop is investigated at different combinations of the plenum chamber design. Lastly, Chapter 5 concludes the present study and offers several recommendations for future studies on the fluidization systems developed prototype.

CHAPTER 2 : LITERATURE REVIEW

2.1 Fluidization

Fluidization would be defined as the process involving fluid passing through a packed bed of solid particles with a certain velocity to produce drag force on the particles to overcome each of the weight of the particles. As a result, the particles will no longer rest on each other and thus will behave and flow like a fluid (Sheng et *al*., 2012). In other words, fluidization is a phenomenon where the solid particle gets transformed into a state where it behaves like a fluid when gas or liquid passes through it. As the flow increases, drag force will also increase accordingly. Finally, at a certain flow rate, the drag is large enough to support the entire weight of the bed. At this point, particles would be declared to be fluidized, and the velocity of the fluid at this instance is referred to as minimum fluidization velocity (Harish and Murthy (2010). Fluidization requires a vessel with a porous base to place the fluid onto the bed, also known as the distributor. Summary of past studies using the fluidization system application has been created by Haron et *al*. (2017). As many researchers have stated, fluidized bed technology has been successfully used to dry wet solid particles. Furthermore, Gupta and Sathiyamoorthy (1999) list the advantages and disadvantages of the fluidized bed in Table 2.3.

Table 2.1 Advantages and disadvantages of fluidization (Gupta and Sathiyamoorthy. 1999)

Advantages	Disadvantages
A high rate of heat and mass transfer under isothermal operating conditions is attainable due to good mixing.	Fine-sized particles cannot be fluidized without adopting some special techniques, and high conversion of a gaseous reactant in a single-stage reactor is difficult.
A fluid-like behaviour facilitates the circulation between two adjacent reactors.	The hydrodynamic features of a fluidized bed are complex, and hence modelling, and scale-up are difficult.
No moving part, and it 1s not a mechanically agitated reactor; hence low maintenance cost.	Generation of fines due to turbulent mixing, gas or liquid jet interaction at the distributor site, and segregation due to agglomeration result m undesirable products.
It is mounted vertically and saves space.	Elutriation of fines and power consumption due to pumping is inevitable.
A continuous process coupled with high throughput is possible.	Sticky materials or reactions involving intermediate products of a sticky nature would defluidize the bed.
No skilled operator is required to operate the reactor.	Highly skilled professionals m this area is needed for design and scale-up.
It is suitable for accomplishing heat-sensitive or exothermic, or endothermic reactions.	Limits on the operating velocity regime and the choice of the particle size range.
It offers ease of control even for large-scale operation	Erosion of immersed surfaces such as heat - exchanger pipes may be severe.
Multistage operations are possible; hence the solids residence time, as well as the fluid residence time, would be adjusted to the desired level	Reactions that require a temperature gradient inside the reactor cannot be accomplished in a fluidized bed reactor.

2.2 Swirling Fluidized Bed

The fluid bed is spinning like a Torbed reactor. It contains a ring bed, and the gas is pumped in a tilted fashion into the distributor blades. This leads to a swirling movement of solids in a confined circular course. If a gas jet enters the bed at the horizontal angle, the vertical component of the speed, $v \sin \theta$ causes the fluidization and the tangential component $v \cos \theta$ in would cause swirl motion of the bed material. When the bed is sufficiently deep, the horizontal momentum of the jet worsens with the jet penetration into the bed and eventually ceases over the distributor at a certain height. But the speed of the jet leaving the bed in a shallow bed would still have two components. In this case, the bed is granules-like.

There is a range of industrial applications focused on a fluidized swirling bed. However, very little literature on this topic is available. In order to achieve swirl motion, Ouyang and Levenspiel (1986) engineered a spiral distributor. This distribution network consisted of overlapping vanes, formed as sectors of a circle with a distance between the vanes. The difference between the neighbouring valves at the outer edge was maximum and nil at the middle of the dispenser. The vanes were arranged such that the air from the vanes could be drained tangentially. The inclined jet from the opening was seen to transmit a spinning movement in a shallow field. However, in a deep bed, the swirling motion is confined to the lower portion of the bed, and bubbling takes place above.

Ouyang and Levenspiel (1986) also performed a comparative analysis with a sintered platform distributor on the characteristics of this distributor, such as the pressure drop, fluidization efficiency, and heat transfer coefficient. The sintered plate has been found to have greater fluidization at low surface speed for low-density solids. On the other hand, the output of a spiral distributor is best at high superficial velocities. However, greater fluidization with spiral distributors would be done at all gas speeds for high-density solids. The pressure drop through the spiral distributor was also found to be smaller than that for the sintered plate distributor. The study by Sheng et *al.* (2012) involves the study of SFB hydrodynamics by one-dimensional modelling. The study involves the investigation on blade inclination angle at the distributor, the number of blades, fluid density, velocity, and the bed weight to show the effect based on fluid velocity leaving the bed, the average velocity of particles, and inclination angle of fluid. The study shows that bed weight has the most influence in their study on hydrodynamics. In addition, it shows the high interaction with the parametric value. Table 2.2 summarizes the summary of their studies on the hydrodynamics of SFB.

Table 2.2: Summary of parametric analysis (Sheng et *al.*, 2012)

Parameters	Impact on Hydrodynamics		
	Fluid velocity leaving the bed (m/s)	Average velocity of particles (m/s)	Inclination angle of fluid with horizontal (degrees)
Blade inclination angle at distributor	Medium	High	High
Number of blades	Low	High	Medium

Fluid Density	Low	High	Medium
Superficial velocity	Medium	High	Low
Bed weight	High	High	High

Binod and Raghavan (2002) conducted experiments with vane tilted to the horizontal at a 12° angle in a swirling room. The difference between blades varied by radius to create a trapezoidal airflow gap. At the base of the bed was a hollow metal ring. Experiments with spherical PVC particles between 3.5 mm and 2.5 mm were carried out. There was a steady decrease in the pressure of the swirling system but a rise in the gas flow volume. In comparison to traditional beds, four operating regimes could be found in a Swirling Fluidized Bed. Bubbling, wave motion, two-layer fluidization, and smooth swirling with the creation of a dome. It was also found that the pressure drop in the fluidized system decreased as the angle of injection, θ.

As Josephkunju (2008) mentioned in Vikram et al.'s (2003) study, they carried out hydrodynamic experiments on a fluidized swirling surface. The velocity of the spinning particles was observed to increase with radial size. It was also observed that both the gas and particle velocity decayed sharply with height. Moreover, Paulose and Nampoothiri (2004) have conducted studies to compare the efficiency of various types of Swirling Fluidized Bed distributors. Experiments have been performed using three distributor types. One row vane type vending machine, 3-row vane type vending machine, and inclined hole type vending machine. The most useful area for the inclined hole style distributor was found. Nevertheless, the pressure decrease for the one-row vane style distributor was the lowest. Further hydrodynamic experiments in Swirling Fluidized Bed were performed by Paulose and Nampoothiri (2005). Distributors of the single-row vane type with vane angles 150 and 200 were adopted. Coffee beans (type D-Geldart) with an average diameter of 8.82 mm and a relative density of 0.75 were examined. The minimum fluidizing velocity has been found to be constant regardless of the angle of the vane. The experimental tests also showed that the pressure drop decreases as the angle of the valve increases.

Madhiyanon et *al.* (2007) developed a new cold combustor model known as the cyclonic fluidized bed combustor that has both the beneficial swirl flow and fluidized bed flow properties. Primary air or vortex air was pumped into the top of the combustion system as a perforated air distributor was used to push secondary air or fluidized air upwards. They observed the development of vortices in the bed, which facilitated fluidization by increasing the upward axial fluid speed without increasing the fluidizing airspeed. Kamil et *al.* (2007) performed a parametric study of an empirical model of a fluidized swirling bed. The effect of the angle of the blade, the hydrodynamic characteristics of the Swirling Fluidized Bed, was investigated on gas density and particle density. The results of the study show that density and gas content of particles are the most significant parameters, followed by blade angle and superficial gas speed.

The literature review provides an overview of the various types of distributors produced for specific processes. The distributor's optimum configuration guarantees consistent airflow and a low-pressure drop in the distributor. The pressure drop rate is also seen as a significant parameter in a distributor's design. This ratio depends on the size of the distributor. The minimum value of the lower pressure ratio ranges from 0.02 to 0.05 for stable fluidization in a deeply fluidized bed. In modern fluidized beds, almost all researchers accept that the drop for bed pressure is constant at a gas speed greater than the minimum fluidizing level, and differences in pressure drop following fluidization are indicative of undesirable characteristics such as sluggishness or channelling.

Based on experimental studies that were carried out with multi-orifice style vendors, the number of operating holes was determined by the gas flow, the bed height, the style of bed material, and the distributor's open area. The mathematical model Fakhimi et *al.* (1983) suggested estimating the number of active orifices at any given flow rate. A variant related studies with pore plate distributors have shown that the consistency of the fluidization is regulated by different properties of the generated bubbles Wormbecker et *al.* (2007); Sutar and Kumar (2012); Agu and Moldstad (2018); Sathyamoorthy et *al.* (2003) conducted experimental studies and concluded that the aspect ratio had a significant impact on fluidizing quality. Several researchers performed various experiments to study the variability of minimum velocity with temperature fluidization. The minimal fluidizing velocity was observed to decrease steadily with a temperature rise for 0.19 mm particles. However, the minimum fluidizing velocity in particles of 2 mm diameter was found to be temperature independent. For particles much greater than 2 mm in diameter, the minimum velocity of fluidization for temperature increased.

Only a few pieces of literature are available in fluidized swirling beds. Experiments with the Swirling Fluidized Bed were performed by Ouyang and Levenspiel (1986), and the pressure dropped as the injection angle increased. Vikram et *al.* (2003) found that radial distance increases in the speed of swirling particles. In Swirling Fluidized Bed experiments Paulose and Nampoothiri (2005) have found that the minimum fluidizing speed in the Swirling Fluidized Bed is constant, similarly to the traditional fluidized bed. Analytical research by Kamil et *al.* (2007) revealed that the density of particles and gas are the most significant parameters in a fluidized spinning sheet. No experimental research on the effect of air injector angle and particles on the hydrodynamic characteristics of a swirling fluidized bed have been carried out to date. Therefore, the current fluidization has been used widely in the industries whereby each system has its own characteristics and proposed more benefit in applications than the conventional fluidized beds. Here, Marimuthu (2011) has listed a few comparisons between the current fluidized bed and the conventional system, as summarized in Table 2.5.

Table 2.3 Comparison between conventional fluidized bed system and Swirling Fluidized Bed (Marimuthu, 2011)

Aspect	Conventional Fluidized Bed	Swirling Fluidized Bed
The direction of fluid flow	Fluid enters into the bed in direction only, which is vertical motion	Fluid enters into the bed in two directions – vertical and horizontal motion
Process	Only have fluidization	Have both swirling and fluidization at the same time
Types of distributor	Perforated or porous plate distributors	Annular spiral distributor
Types of fluidization	Good fluidization require a high distributor pressure drop	Quality fluidization is achieved with a comparatively lower distributor pressure drop

Limitations	Limitations such as slugging, channelling, elutriation of solid particles, limitations in the size of particles	Limitation due to the use of the annular area of the distributor, which causes a restriction in its size

2.3 Distributors in Fluidization Systems

The gas distributor's output also dictates the success or failure of a fluidized bed. The reckless construction of or malfunctioning gas distributors normally leads to extreme difficulties in fluidized beds (Geldart and Baeyens 1985). Solid processing requires the rapid dispersion of solid feeds, which prevents the secretion which denser particles from settling on the distributor that would cause the entire bed to differ at varying temperatures and fast defluidize. In applications where high conversions are required, uniform gas delivery and small grid bubbles are of major importance. The efficient design of the distributor would therefore play a crucial role in improving the fluidization process, including the pressure drop ratio, hole size, structure, spacing, and dead areas. The idea of the annular distributor was introduced by the spiral distributor, which is suggested by Ouyang and Levenspiel (1986), as shown in Figure 2.1.

The work of Sreenivasan and Raghavan (2002) was the pioneering aspect of the hydrodynamic characteristics in a Swirling Fluidized Bed studied on an experimental and analytical model to Kaewklum and Kuprianov (2009) studied. The same principle from Shu et *al.* (2000) the inclination of gas into the fluidized particle bed through the use of a ring blade creates a tangential movement in the field, which overcomes some unique shortcomings in the traditional shallow bed at the swirling zone; no bubbles are seen, and no gas can passes through. Sreenivasan and Raghavan (2002) claimed that the annular distributor would lower the centrifugal force radial variation as opposed 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.

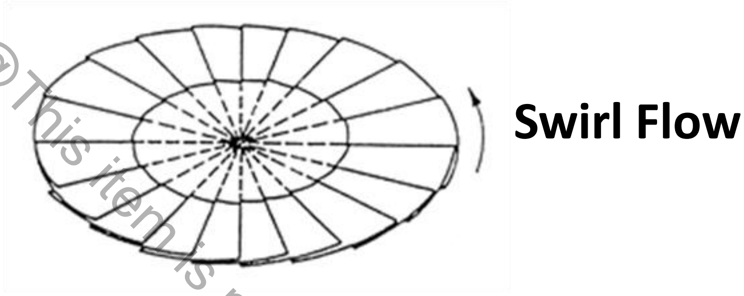

Figure 2.1 The annular spiral distributor and airflow are counterclockwise (Ouyang and Levenspiel, 1986).

The gas has a slightly longer travel than the height of the bed due to a helical path, and the movement of the particles does not rely on bubbles. Therefore, the feed spreads rapidly and deeply in the bed at one level of the swirling sheet (Sreenivasan and Raghavan, 2002). However, fluid density influences are the most significant factor, followed by the blade angle and superficial gas speed (Kamil et *al.*, 2007). A similar study has been done by Batcha, Salleh, and Raghavan (2009) were focusing on different blade distributor configurations by using an annular blade distributor with blades gap on a various number of overlapping blades design as shown in Figure 2.2 The blades inside the SFB systems is in hydraulic diameter (d_h), where d_o is outer diameter and d_i is the inner diameter of the SFB wall system. Due to the gap, the trapezoidal cross-section area was formed, where the blade gap was smaller, X_i at inner diameter and largest X_o at the SFB wall for the air flowing through between two consecutive blades. The Swirling Fluidized Bed has potential for broad industrial uses; very few comprehensive studies of such a bed are available even though the concept was already used in commercial equipment. As the safe mixing regime without bubbles and consequently gas passes slugging, swirl bed has a promising future for the production of solid gas. From this study, (Batcha, Salleh, and Raghavan, 2009) discovered that the bed pressure drop increased at superficial velocity after limited fluidization, as opposed to the conventional fluidized bed. The blade geometries have also been found to have less impact on bed efficiency than a fraction of open area and particle size, as shown in Figure 2.2.

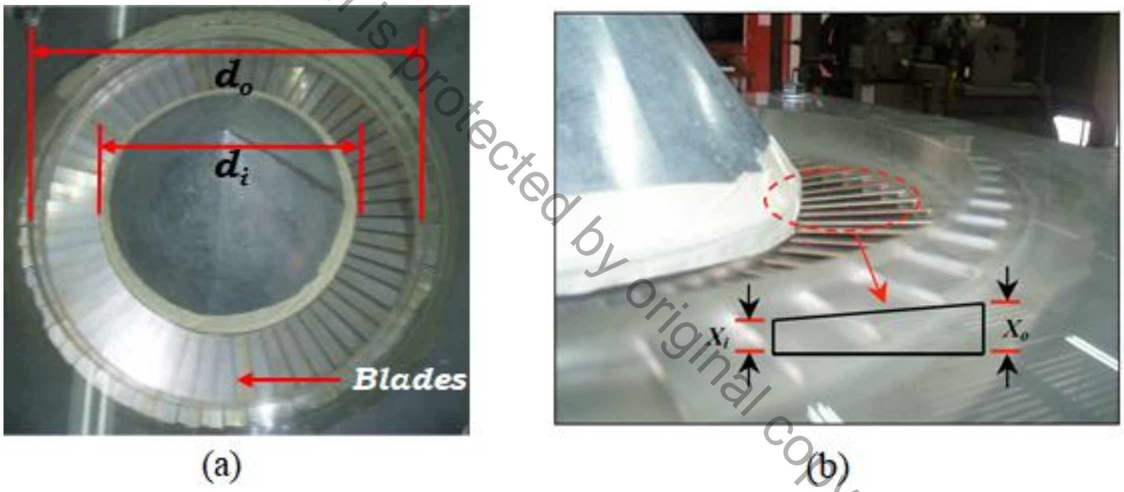

Figure 2.2: Configuration of blade SFB; (a) annular blades distributor of the SFB (b) Blade arrangement and trapezoidal opening in the SFB distributor (Batcha, Salleh and Raghavan, 2009).

Kamil et *al.* (2007) studied the relative significance of operational parameters on the hydrodynamic characteristics of Swirling Fluidized Bed. The two-dimensional (2D) analytical model investigating the effect on blade angle, gas, and particle density is of greatest importance in the study of gas and particle density followed by the blade angle.

The comparison of experiments from the previous to the current study is shown in Table 2.4. The initial concept of an annular distributor has been proposed by Ouyang and Levenspiel (1986). Based on this new idea, several researchers have shown an interest in further analysis through various parametric studies.

Table 2.4 Experimental details for the comparison of the type of plenum chamber.

Researchers	Type of Plenum Chamber	Number of Blade Distributor	The Angle of Inclination of Blade
Ouyang and Levenspiel (1986)	-	24 and 32	Not Stated
Wellwood (2000)	Tangential Entry	Not Stated	10°, 20° and 30° (Horizontal)
Shu et *al*. (2000)	Axial Entry	Not Stated	25° (Horizontal)
Sreenivasan and Raghavan (2000)	Tangential Entry	60	12° (Horizontal)
Keawklum et *al*. (2009)	Axial Entry and Tangential Entry	11	14°
Kaewklum and Kuprianov (2009)	Axial Entry	11	14°
Chakritthakul et *al*. (2011)	Axial Entry	22	14°
Batcha and Raghavan (2011)	Tangential Entry	30 and 60	9° and 12° (Radial)
Vinod et *al*. (2011)	Tangential Entry	60	15° (Horizontal)
Sheng et *al*. (2012)	Radial Entry	60	10° (Horizontal)
Venkiteswaran et *al*. (2012)	Tangential Entry	60	9° (Radial) with 10° (Horizontal)
Arromdee and Kuprianov (2012)	Axial Entry	11	14°
Miin et *al*. (2015)	Tangential Entry	60	15°