



**Influence of Slotted Inclination Angle on  
Velocity Characteristics in Fluidization Systems via  
Computational Fluid Dynamics Analysis**

by

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## LIST OF ABBREVIATIONS

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

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## LIST OF SYMBOLS

$D_{PC}$	Plenum chamber diameter
$D_I$	Internal diameter tangential entry
$E_D$	Entry inlet diameter
$H_{PC}$	Plenum chamber Height
$g$	Gravitational acceleration
$m$	mass of particles
$P$	pressure
$P_I$	pressure at the facet average
$P_r$	pressure reference
$R_P$	radius of slotted distributor
$v_r$	radial velocity
$v_\theta$	tangential velocity
$v_z$	axial velocity
$v$	free stream velocity
$v_c$	centre velocity
$\mu$	kinematics viscosity
$\rho$	density
$\rho_f$	fluid density
$\rho_p$	density of particles

## Pengaruh Pengedar Plat Berongga Terhadap Sifat-Sifat Halaju Dalam Sistem Pembendaliran Melalui Analisis Pengkomputeran Dinamik Bendalir

### ABSTRAK

Pembendaliran adalah proses di mana zarah pepejal tergantung dalam keadaan seperti bendalir dan digunakan secara meluas dalam penjaan kuasa, proses kimia, industri pemprosesan mineral, proses pengeringan dan lain-lain. Kajian-kajian ini dilakukan 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 bendalir 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 pengedar yang memfokuskan pada sudut kecenderungan berongga dan jumlah pengedar plat berlubang, (ii) Keupayaan untuk mengesahkan komponen halaju pada pengedaran aliran udara dengan menggunakan reka bentuk pengedar plat berongga, dan (iii) Menilai keupayaan geometri optimum pengedar plat berongga melalui kaedah pengoptimuman yang memfokuskan pada 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 plat berongga dengan bilangan slot yang berbeza-beza (10, 12 dan 14) dan pelbagai sudut kecondongan berongga ( $15^\circ$ ,  $45^\circ$  dan  $90^\circ$ ). 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)*. Hasil pemerhatian mendapati penemuan yang paling signifikan dalam kajian ini yang mewakili reka bentuk optimum pengedar berongga dalam sistem pembendaliran yang masing-masing adalah seperti sudut condong berongga  $45^\circ$  dan 10 nombor berongga. Reka bentuk optimum ini telah membentuk keseragaman halaju dengan tinggi halaju tangen adalah 24.39 m/s dengan sisihan piawai yang rendah 3.7% dan penurunan tekanan yang lebih rendah iaitu 2817.24 Pa. Selain itu, analisis lanjutan melalui kaedah pengoptimuman dengan menggunakan ANOVA telah menunjukkan bahawa sudut kecenderungan berongga mempunyai parameter yang signifikan pada nilai-nilai halaju tangen dan penurunan tekanan. Berdasarkan hasil ANOVA, penurunan tekanan adalah parameter yang paling signifikan yang menyumbang kepada penggunaan tenaga yang lebih rendah pada sistem pembendaliran.

## **Influence of Slotted Inclination Angle on Velocity Characteristics in Fluidization Systems Via Computational Fluid Dynamics Analysis**

### **ABSTRACT**

Fluidization is the process in which solid particles are suspended in a fluid-like state and widely used in power generation, chemical process, mineral processing industries, drying process and etc. These studies are carried out due to the constraints on conventional fluidization system which can be inferred to; (i) Several type of distributor designs, which can influence the bubble size and lowers the fluidization performance, (ii) The conventional fluidization systems does not fluidize at one specific value thus directly affecting the bed behavior, and (iii) The pressure drop in conventional fluidization is not constant with increasing air velocity; affecting bed weight or bed moisture content. Therefore, the current study aims to; (i) Ability to assess the operational range of several types of distributor that focus on slotted inclination angle and slotted number of perforated plate distributor, (ii) Ability to verify the velocity component on airflow distribution of a current perforated plate distributor design, and (iii) Ability to evaluate the optimum geometry of perforated plate distributor via optimisation method that focuses on low pressure drop, uniform velocity and high tangential velocity. In order to achieve the goal outlined, several methods have been proposed in these studies. Firstly, the numerical simulation of Computational Fluid Dynamics (CFD) was used to investigate the parameters that can influence the perforated plate distributor with varying slot numbers (10, 12 and 14) and at various slotted inclination angles ( $15^\circ$ ,  $45^\circ$  and  $90^\circ$ ). Secondly, the CFD is used to investigate the velocity characteristics of each velocity component such as velocity magnitude, tangential velocity, axial velocity and radial velocity as well as the pressure drop effected by slotted distributor configuration. And thirdly, the extracted data was evaluated by using statistical analysis on mean values, standard deviation, and also using an optimisation method like Full Factorial Design (FFD). It has been observed that the most significant findings in this study which represent the optimum design of a perforated plate distributor in a fluidization system were  $45^\circ$  angled slot inclination and 10 slots number respectively. This optimum design has formed a velocity uniformity with a higher tangential velocity of 24.39 m/s with a low standard deviation of 3.7% and a lower pressure drop of 2817.24 Pa, respectively. Moreover, extended analysis via optimisation method using ANOVA has shown that slotted inclination angle has significant parameter on the values of mean tangential velocity and pressure drop. Based on the ANOVA results, pressure drop is the most significant contributing parameter in lessening energy consumption on the fluidization systems.

## CHAPTER 1 : INTRODUCTION

### 1.1 Background and Research Motivation

Fluidization is a new technique with various advantages and can be applied on various desirable properties in vast 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 the forces. These forces may be sufficiently strong to destabilise the particle structure in the bed. Even if the fluid velocity is increased, the fluid drag maintains the total weight of the particles.

Fluidization is applied in many drying processes, for example in agricultural sector for drying black pepper, cocoa beans and coffee beans. Since drying rate and thermal efficiency both have their added 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 large area of interaction between the particles and the air. It will also ensure that the mixture has a homogeneous blend of solids and uniformly distributed moisture composition. Due to its rapid drying, this was a cheap drying procedure compared to other drying methods. Another possible aspect is that solids can be added or removed to improve the process.

However, there are several limitations to the approach. These include limiting the flow of gas to ensure that the fluidized bed does not lose part of its elutriation as a result

of bubbling gas fluidized bed. Limitation to the fluidization is the bed's exact force must be maintained and for efficient fluidization, there are constraints on particle size, size distribution, and shape.

There has been numerous efforts directed towards rectifying the issues associated with conventional fluid beds and improving their uniformity. Developing these kinds of fluidized beds such as circulating fluidized bed, tapered fluidized bed, centrifugal fluidized bed, spotted fluidized bed and swirling fluid bed, had created numerous forms of fluidized bed equipment. More recent designs for fluidized beds have been developed considering the adverse side effects observed in current fluidized beds.

Most recent technology used in the current study is Swirling Fluidized Bed (SFB). Compared to SFB, 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 own swirling motion (Sreenivasan et al., 2002). On the other hand, the SFB has its limits because most SFBs employ annular distributor that only has an annular region, which eventually limits the overall size of the distributor.

The present work introduces and studies components of a gas velocity that would continuously fluidize bed incorporating an annular blade distributor, angular gas injection, and swirling motion of bed material in a circular path as shown in Figure 1.1. There are several advantages in continuing the studies on the annular blade distributor in the SFB system; when injecting gas at an angle, a swirling bed would function at a higher tangential velocity with less elutriation. This condition may cause the annular blade

distributor design, the gas injection angle or the vertical flow of gas entering the bed is much smaller in SFB compared to a horizontal flow. The distributor's sophisticated design ensures efficient gas distribution without imposing excessive resistance on the flow of gas. In real industry application, the particles are pushed outwards by centrifugal force, which pulls them away from the centre and towards the outside wall, where the upward gas velocity is lower (Sreenivasan et al., 2002). As the air velocity increases, the swirling in the middle of the bed impairs the passage of particles from the centre to the outer wall. Gas bypass may occur in an empty region created towards the inner wall of the column.

Usually, the flow rate of gas entering the bed can be separated into three velocity components: axial, radial and tangential. These three velocity components could be described as an axial velocity, produces fluidization while tangential velocity offers swirling effect in industrial applications. Due to the swirl, gas experiences centrifugal force, that is the source of the radial velocity. Figure 1.1 shows the normal configuration of SFB. Here the gas is horizontally injected into the bed at a certain blade angle. The velocity of the gas would be measured in vertical dimension of  $v \sin \alpha$  and in horizontal component  $v \cos \alpha$ . The vertical component causes fluidization, which swirls the horizontal component (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 & Raghavan, 2011) have conducted experiments in SFB, and the resultant study findings show that radial distance increases the velocity of swirling particles.

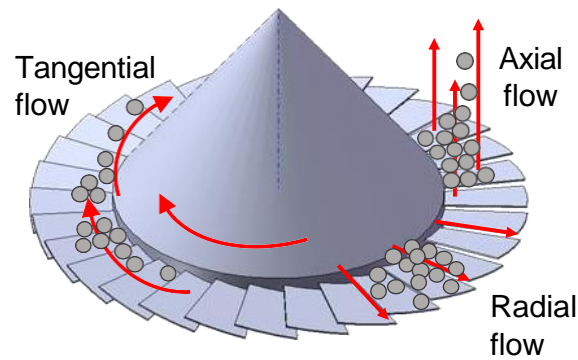


Figure 1.1: Annular Blade Distributor of Swirling Fluidized Bed

While using the annular blade distributor, like in the SFB system, there is the pressure drop restriction. Paulose (2006) examined SFB from different distributors and concluded that the pressure drop of the distributor is the lowest for the annular blade distributor design. 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 minimised. More comprehensive processing is possible due to improved preservation of the particles and temperature. Bigger particles that is difficult to fluidize (Goldart D type) in a conventional bed would be effectively fluidized in swirling fluid beds.

Further analysis will be carried out with computer simulation using the ANSYS Fluent software programmer. The problem will be further investigated by modifying the annular blade distributor in order to determine the high tangential velocity and contribute to adequate air flow distribution. Computer modelling 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 influence the performance of the fluidization. If the huge bubbles occurred, gas solid contact will reduce. Numerous design parameters, such as distributor design, can influence the bubble size and fluidization performance. In addition, this swirl of fluid particles formed because of the distributor design. When the gas progresses deeper into the bed, it loses its horizontal momentum, and after a certain point it simply ceases to exist above the distributor. 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 occurred to the airflow behavior in fluidization systems that can proposed an intense mixing by setting different annular blade distributor depth in the plenum chamber.

One that is involved with Swirling Fluidized Bed, if the horizontal momentum of the air jet is sufficiently decreased as the air jet is penetrates deep into the bed and the 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, shearing has occurred between the particles and the air. 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 swirling layer 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 as well. Only the outer annular space can be used in a swirling fluidized bed due to vortex formation accompanied by swirl motion. This result was decrease in the usable area of the blade distributor. The high 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 annular blade distributor is a modern idea that makes it possible to increase the usable area of the distributor, which forms as 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 compared to 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 date very lack studies have been carried out in a fluidized bed field especially on configuration of blade design via numerical study. As the explanation above was referred to the objective (i).

There are challenges with applying annular blade distributor as in the fluidized bed system due to various swirling flow motion. Due to the restriction in its size, only an annular zone of the distributor is utilised in a fluidized bed in swirling motion. The important impact on the minimum fluidization velocity as well as swirl velocity is the angle of the air jet. There is the potential for some of the 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 air flow 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. Normally the previous researcher only discussed the mixing of airflows

that occurred due to the high tangential velocity component. And, some researcher that involved with annular blade distributor has small knowledge on how the characteristic on airflow during mixing. Due to these limitations, the current study used CFD simulation as its method analysis. As the explanation above was referred to the objective (ii).

The conventional fluidization, where the distributor is in perforated plate type will have an effect on the flow pattern and the mixing in the plenum chamber. As a result of this factor, the current study was more interested to investigating the current airflow behaviour by using the annular blade distributor compared to the conventional distributor fluidized bed. For example, the Wormsbecker et al. (2007) study involved with the conventional distributor (perforated plate, wire mesh and punched plate). As the researcher has reported, that punched plate consists of hooded openings that forms rings in a circular pattern. The punched plate distributor was form in 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 was not suitable for low cost operations. Another related study proposed by Batcha and Raghavan (2011) on the new type distributor that was mimics of blades turbine has blade inclination angle ( $9^\circ$  and  $12^\circ$ ) and blade inclination length ( $15^\circ$  and  $18^\circ$ ) at each blades distributor. At blade inclination lengths, the higher distributor pressure drops occurred due to greater inclination lengths, which constrain the airflow in much longer between the blades before flowing smoothly to the beds. This condition can also be defined as having an airflows facing the impingement wall (high resistance) before the air passes through the gap between the blades distributor. Naturally, the higher number of inlets has a higher-pressure drop due to an increase in the 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. Reduction of the bed pressure is crucial for the determination of the power required in industrial processes involving gas-solid contact. Based on this air flow characteristic, assessing by statistical analysis, it may reveal how much variance in a dependent variable would be affected by the independent variable. As the explanation above was referred to the objective (iii).

### **1.3 Research Questions**

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

- i. What is the most significant configuration that influences minimum velocity fluidization and velocity uniformity in the fluidization system?
- ii. How much is the sufficient current fluidization design in terms of high velocity retention as compared to different annular distributor blade depth?
- iii. What are the optimal parameters' settings that contribute to low pressure drop and high air flow distribution at different annular blade distributor depth at the current fluidization design?

### **1.4 Research Objective**

The main objectives of these studies are.

- i. Ability to assess the operational range of slotted inclination angle and slotted number for perforated plate distributor in a fluidization system.
- ii. Ability to verify the air flow behaviour of velocity distribution on the perforated plate distributor with regard to fluid flow profiles at various operating conditions through CFD simulation.
- iii. Ability to evaluate the optimum geometry of perforated plate distributor via optimisation method of Full Factorial Design (FFD) towards uniform velocity, high tangential velocity and low pressure drop.

## 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 simulation analyses of the perforated plate distributor, which included both airflow distribution and pressure drop studies. The investigation is constrained by physical constraints in  $R_{PC}/D_E \leq 2.0$ .
- ii. The simulation performance of the perforated plate distributor may only be rated through velocity component formation (tangential velocity) and pressure drop. Intended to determine the optimum dimensions, such as diameter and height of plenum chamber, tangential entry type of plenum