Influence of Spiral Blade Distributor on the Airflow Distribution in Fluidisation Systems via Computational Fluid Dynamics Analysis

by

Muhammad Lutfi Bin Abd Latif
(1931413060)

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Faculty of Mechanical Engineering Technology
UNIVERSITI MALAYSIA PERLIS

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May Almighty Allah Bless You All

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LIST OF ABBREVIATIONS

2D	Two-dimensional
3D	Three-dimensional
ANN	Artificial Neural Network
ANOVA	Analysis of Variance
ANSYS	Analysis System
AV	Axial Velocity
CAD	Computer-Aided Design
CFD	Computational Fluid Dynamic
DOE	Design of Experiments
FFD	Full Factorial Design
FOA	Fraction of Open Area
GA	Genetic Algorithm
GNF	Generalised Newtonian Fluid
GAMBIT	Geometry and Mesh Building Intelligent Toolkit
HJIS	Horizontal Jets and Inclined Surfaces
IGES	Initial Graphics Exchange Specification
PTV	Particle Tracking Velocimetry
PVC	Polyvinyl Chloride
RANS	Reynolds Averaged Navier Stokes
RMSD	Root Mean Square Deviation
RNG	Re-Normalisation Group
RSM	Response Surface Methodology
RSM	Reynold Stress Models
RTD	Residence Time Distribution

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RV	Radial Velocity
SFB	Swirling Fluidized Bed
SST	Shear Stress Transport
TV	Tangential Velocity
VM	Velocity Magnitude

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LIST OF SYMBOLS

A	Cross-sectional area of the bed
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_1	Pressure at the facet average
P_r	Pressure reference
R_P	Radius of slotted distributor
R_e	Number of Reynolds
k	Turbulent kinetic energy
ε	Rate of dissipation of turbulent kinetic energy
v_r	Radial velocity
v_θ	Tangential velocity
v_z	Axial velocity
v	Free stream velocity
v_c	Centre velocity
μ	Kinematics viscosity
ω	Specific turbulent dissipation rate
ρ	Density of the fluid
ρ_f	Fluid density
ρ_p	Density of particles

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θ	Angle
Δ	Difference
ΔP	Pressure drop
U	Fluid velocity
$\mathrm{U}mf$	Minimum fluidization velocity
ψ_1	First normal stress coefficient
ψ_2	Second normal stress coefficient
τ	Shear stress
$\dot{\gamma}$	Strain rate
t	Time

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Pengaruh Pengedar Bilah Lingkaran Terhadap Agihan Aliran Udara Pada Sistem Bendalir Terpusar Dengan Analisis Pengkomputeran Dinamik Bendalir

ABSTRAK

Pengedar bilah dalam sistem pembendaliran berpotensi tinggi untuk digunakan secara meluas dalam industri penjanaan tenaga, pemprosesan mineral, dan kimia. Oleh itu, penggunaan suntikan gas condong dalam pengedar bilah akan menunjukkan prestasi yang lebih tinggi dalam sistem pembendaliran. Kajian terdahulu membuktikan terdapatnya beberapa kekangan dalam sistem pembendaliran konvensional seperti; (i) beberapa jenis reka bentuk pengedar dapat mempengaruhi ukuran gelembung dan menurunkan prestasi pembendaliran, (ii) sistem pembendaliran konvensional tidak membendalir pada satu nilai tertentu dan mempengaruhi kelakuan *bed* secara langsung, dan (iii) penurunan tekanan dalam pembendaliran konvensional tidak konsisten dengan peningkatan halaju udara yang akan mempengaruhi berat *bed* atau kandungan kelembapan *bed.* Oleh yang demikian, kajian semasa ini bertujuan untuk; (i) menilai keupayaan jangkauan operasi beberapa jenis pengedar yang memfokuskan sudut kecenderungan bilah dan jumlah pengedar plat berlubang, (ii) keupayaan untuk mengesahkan komponen halaju pada pengedaran aliran udara dengan menggunakan reka bentuk pengedar bilah lingkaran, dan (iii) menilai keupayaan geometri optimum bagi pengedar bilah lingkaran melalui kaedah pengoptimuman iaitu penurunan tekanan rendah, halaju seragam, dan halaju tinggi tangen. Untuk mencapai tujuan yang digariskan ini, kajian ini telah mencadangkan beberapa kaedah. Pertama, simulasi berangka Pengkomputeran Dinamik Bendalir *(CFD)* digunakan untuk menyiasat parameter yang mempengaruhi pengedar bilah lingkaran dengan panjang sela yang berbeza-beza (60 mm, 80 mm, dan 100 mm) dan pelbagai sudut kecondongan mendatar (0°, 12°, dan 15°). Kedua, *CFD* digunakan untuk mengenal pasti ciri-ciri halaju bagi setiap komponen halaju, seperti magnitud halaju, halaju tangen, halaju paksi, dan halaju radial serta penurunan tekanan yang dilakukan oleh konfigurasi pengedar bilah lingkaran. Ketiga, data yang dikeluarkan telah dinilai menggunakan analisis statistik pada nilai purata, sisihan piawai, dan kaedah pengoptimuman seperti *Full Factorial Design (FFD).* Penemuan paling signifikan dalam kajian ini yang mempengaruhi reka bentuk sistem pembendaliran semasa adalah sudut kecondongan bilah pada 12° dengan panjang sela sebanyak 100 mm. Reka bentuk optimum ini telah membentuk keseragaman halaju dengan halaju tangen yang tinggi pada 21.018 m/s dengan sisihan piawai yang rendah iaitu 2.996% dan penurunan tekanan yang lebih rendah iaitu 3593.59 Pa. Seterusnya, analisis lanjutan dengan menggunakan Analisis Varians (ANOVA) telah menunjukkan bahawa sudut kecondongan bilah mempunyai parameter yang signifikan pada nilai-nilai halaju tangen dan penurunan tekanan. Berdasarkan faktor sudut kecondongan mendatar dan panjang sela pengedar bilah lingkaran, penurunan tekanan pada sistem pembendaliran semasa adalah parameter paling signifikan yang menyumbang kepada penggunaan tenaga yang optimum dalam sistem pembendaliran.

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Influence of Spiral Blade Distributor on the Airflow Distribution in Fluidisation Systems via Computational Fluid Dynamics Analysis

ABSTRACT

Blade distributors have a huge potential to be widely used in fluidisation systems in the power generating, chemical, and mineral processing sectors. The use of slanted gas injection in the blade distributors would attain greater performance in the fluidisation systems. Previous studies have been carried out to address various constraints of conventional fluidisation systems. One of the concerns is that the distributor design can influence the bubble size and reduce the fluidisation performance. In addition, conventional fluidisation systems do not fluidise at one specific value that directly affects the bed behaviour. The pressure drop in conventional fluidisation is also inconsistent with the increasing air velocity, which affects the bed weight or bed moisture content. Therefore, the current study was aimed to assess the operational range of several types of distributors by focusing on the blade inclination angle and the pitch length of the spiral blade distributor. The current study also verified the velocity component of the airflow distribution using the current perforated plate distributor design. Furthermore, the optimum geometry of the perforated plate distributor was evaluated via the optimisation method, in particular, the low-pressure drop, uniform velocity, and high tangential velocity. Several methods have been proposed to achieve the goal outlined in this study. First, the numerical simulation of Computational Fluid Dynamics (CFD) was used to investigate the spiral blade distributor in the fluidisation system with varying pitch lengths (60 mm, 80 mm, and 100 mm) and various horizontal inclination angles (0°, 12°, and 15°). Second, the CFD was 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 of the spiral blade distributor configuration. Third, the extracted data were evaluated using statistical analysis based on mean values, standard deviation, and optimisation method, including the Full Factorial Design (FFD). The most significant finding in this study that represents the optimum design of the spiral blade distributor fluidisation system was the 12° inclination angle with a pitch length of 100 mm. The findings in this study showed that the optimum design formed a velocity uniformity with a higher tangential velocity of 21.018 m/s with a low standard deviation of 2.996% and a lower pressure drop of 3593.59 Pa. Furthermore, the extended analysis using the Analysis of Variance (ANOVA) indicated that the blade inclination angle was a significant parameter that influenced the values of the mean tangential velocity and pressure drop. Based on the horizontal inclination angle and the pitch length of the spiral blade distributor, the pressure drop was the most significant parameter that contributed to the reduced energy consumption in the fluidisation system.

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CHAPTER 1: INTRODUCTION

1.1 Background and Research Motivation

Fluidisation is a new technique with advantageous and desirable properties for a wide range of industrial applications, including drying, combustion, biomass gasification, oxidation, metal surface treatment, catalytic and thermal cracking, and coatings. Generally, fluidisation is the process of suspending solid particles in a fluid-like state while being subjected to several forces, such as gravity, buoyancy, and drag, which may be sufficiently strong to destabilise the particle structure in the bed. When the fluid velocity is increased, the fluid drag maintains the total weight of the particles.

The fluidisation system is used in many drying processes, for example, in the agricultural sector such as black pepper, cocoa beans, and coffee beans. Since both the drying rate and thermal efficiency have their advantages, a fluid surface is included in the drying process. The high heat and mass transfer rate between the gases and the particles are conceivable due to the large area of interaction between the particles and the air. This also ensures that the mixture has a homogeneous blend of solids and uniform moisture distribution in the mix. Due to its rapid drying, the fluidisation system is considered a cheap drying method compared to other drying methods. Another advantage of this method is that the solids can be added or removed.

However, there are several limitations to the approach, including the limited flow of gas to ensure that the fluidised bed does not lose part of its elutriation as a result of the typical

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bubbling gas fluidised bed. In addition to the constraints on particle size, size distribution, and shape, the exact force limit of the bed must be maintained for efficient fluidisation. Realising the various drawbacks, there have been numerous efforts towards rectifying the issues associated with conventional fluid beds and improving their uniformity. Various forms of fluidised bed equipment have been developed, such as circulating fluidised bed, tapered fluidised bed, centrifugal fluidised bed, and spotted fluidised bed. Further recent designs of fluidised beds have also been developed considering the adverse side effects that were observed in current fluidised beds.

Among the recent technology that has attracted interest is the Swirling Fluidised Bed (SFB). The SFB is a fascinating fluidised bed technique that utilises gas distributed at a specific angle and combined with fluidising to produce a swirling effect in the fluidisation zone. In other words, after the gas flow has been separated into vertical and horizontal components, each gas flow may be accountable to create its swirling motion (Sreenivasan *et al*., 2002). Despite its significant advantages, the SFB has several distinct limitations. Since most SFBs employ an annular distributor, therefore the system has only an annular region, which limits the overall size of the distributor.

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The present work introduced and studied the components of a gas velocity that would provide a continuous fluidised bed with incorporated annular blade distributor, angular gas injection, and swirling motion of bed material in a circular path, as shown in Figure 1.1. Several advantages have been discovered through continuous studies on the annular blade distributor in the SFB system. When injecting gas at a specific angle, a swirling bed would function at a higher tangential velocity with less elutriation. This condition may be due to the annular blade distributor design and the gas injection angle, where the vertical flow of gas entering the bed is much smaller in an SFB compared to a horizontal flow. The sophisticated design of the distributor ensures an efficient gas distribution without imposing excessive resistance on the flow of gas. In real indusial application, the particles are pushed outwards by a centrifugal force, which pulls them away from the centre and toward 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 hinders the passage of particles from the centre to the outer wall. 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 velocity components: axial, radial, and tangential. These three components could be described as an axial velocity that produces fluidisation, while the tangential velocity offers the swirling effect in industrial applications. Due to the swirl, the gas experiences a centrifugal force, which becomes the source of the radial velocity. Figure 1.1 shows the normal configuration of the SFB. Firstly, 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 ($v \sin \alpha$) at and in the horizontal component ($v \cos \alpha$). The vertical component causes liquidation, which makes the horizontal component swirl (Paulose, 2006). SFB offers many advantages over other conventional fluidised beds. Besides the absence of bubbles and bypass gas in the swirling field, previous studies on SFB have demonstrated that the radial distance increases the velocity of the swirling particles (Batcha and Raghavan, 2011).

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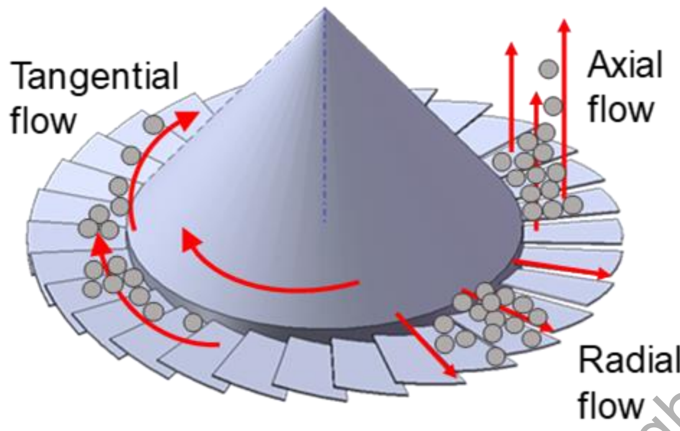

Figure 1.1: Annular blade distributor of SFB

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The use of the annular blade distributor as in the SFB system causes a pressure drop restriction. Paulose (2006) examined the performance of SFB using different distributors and concluded that the pressure drop was the lowest when the annular blade distributor was included in the SFB 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 post-fluidised beds, which makes it an additional advantage since the size of the system could be minimised. Further comprehensive processing is possible to improve the preservation of the particles and temperature. Big particles that are difficult to be fluidised (Goldart D type) in a conventional bed would be effectively fluidised in the SFB system.

The analysis was carried out using a computer simulation using the ANSYS Fluent software programmer. The problem was investigated further by modifying the annular blade distributor in order to determine the high tangential velocity and contribute to an adequate airflow distribution. Moreover, computer modelling was performed to compare the three velocity and pressure drop components based on predetermined parameters.

1.2 Problem Statement

Several distinct flow patterns/regimes in conventional fluidised beds with increasing gas velocity have been observed (such as fixed bed, particle fluidisation, bubbling, slugging, and turbulent fluidisation). Based on the distributor design, the issue of bubble production and eruption in bubbling fluidisation makes it difficult to define the gas flow. Moreover, the size of the bubbles can influence the performance of fluidisation. If huge bubbles are produced, the gas-solid contact would be reduced. Numerous design parameters, such as distributor design, can influence the bubble size and fluidisation performance. In addition, the swirling of fluid particles is 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. Hence, it must be shallow enough for the bed to move in a circular motion. A thorough investigation is required to understand the mechanism of the airflow behaviour in fluidisation systems that can be proposed for intense mixing by setting different annular blade distributor depths in the plenum chamber.

If the horizontal momentum of the air jet in SFB is sufficiently decreased, the air jet would penetrate deep into the bed and eventually end at a certain height above the distributor. In this condition, the bed vortices act as a single unit of mass. As a result, the particles are strongly swirled, causing shearing between the particles and the air. All transport processes have been strengthened. In comparison to the conventional fluidised bed with multiples operating regimens, an SFB is present. Deep beds consist of a two-layered fluidisation 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

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