



**Effect of Twist Blade Distributor on the Velocity  
Distribution using Computational Analysis for  
Swirling Fluidized Bed**

by

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## TABLE OF CONTENTS

	<b>PAGE</b>
<b>DECLARATION OF DISSERTATION</b>	<b>i</b>
<b>ACKNOWLEDGEMENT</b>	<b>ii</b>
<b>TABLE OF CONTENTS</b>	<b>iii</b>
<b>LIST OF TABLES</b>	<b>vi</b>
<b>LIST OF FIGURES</b>	<b>vii</b>
<b>LIST OF ABBREVIATIONS</b>	<b>x</b>
<b>LIST OF SYMBOLS</b>	<b>xi</b>
<b>ABSTRAK</b>	<b>xii</b>
<b>ABSTRACT</b>	<b>xiii</b>
<b>CHAPTER 1 : INTRODUCTION</b>	<b>1</b>
1.1 Introduction	1
1.2 Background of Study	2
1.3 Problem Statement	3
1.4 Objective	4
1.5 Scope of Study	5
1.6 Significance of Study	5
<b>CHAPTER 2 : LITERATURE REVIEW</b>	<b>6</b>
2.1 Fluidization	6
2.2 Drying of Agro Product in Fluidized Bed	11
2.3 Swirling Fluidized Bed	12

2.4	Distributor in Fluidized Systems	17
2.4.1	Distributor Pressure Drop	21
2.4.2	Perforated Plate Pressure Drop	22
2.5	Air Flow Distribution in a Swirling Fluidized Bed	24
2.5.1	Computational Fluid Dynamic (CFD) Analysis in Swirling Fluidized Bed	25
2.5.1.1	Plenum Chamber and Hub Geometries	26
2.5.2	Particle Image Velocimetry (PIV) Analysis of Air Distribution	27
2.6	Turbulence Model	29
2.7	Governing Equation	31
	<b>CHAPTER 3 : METHODOLOGY</b>	<b>33</b>
3.1	Numerical Methodology	33
3.2	SolidWorks Software	33
3.2.1	Number of Blade	33
3.2.2	Angle of Blade	35
3.3	Pre-processing: Geometry and Mesh	35
3.3.1	Boundary Type	36
3.3.2	Meshing	36
3.4	Solver: Solution Techniques	37
3.4.1	Boundary Conditions	38
3.4.2	Grid Sensitivity Study	38
3.4.3	Running the Simulation	39
3.5	Post-Processing: Results	40
3.6	Flowchart of Simulation	41
	<b>CHAPTER 4 : RESULTS AND DISCUSSION</b>	<b>42</b>
4.1	Introduction	42
4.2	Grid Sensitivity Study	42

4.2.1	Meshing Scheme Study	43
4.2.2	Results of Grid Sensitivity Study	45
4.3	Design of Experiment (DOE)	45
4.3.1	The Response of Mean Tangential Velocity	46
4.3.2	The Response of Pressure Drop	48
4.4	Pressure Drop	51
4.5	Velocity Distribution	54
4.6	Tangential Velocity Distribution	57
4.7	Radial Velocity Distribution	59
4.8	Axial Velocity Distribution	61
4.9	Statistical Analysis	64
4.9.1	High Mean Tangential Velocity	64
4.9.2	Uniformity of Tangential Velocity Distribution	66
4.9.3	Low Pressure Drop	67
4.10	Determining an Optimum Bed Design	68
4.11	Summary	69
	<b>CHAPTER 5 : CONCLUSION AND RECOMMENDATION</b>	<b>71</b>
5.1	Conclusion	71
5.2	Recommendation for Future Studies	72
	<b>REFERENCES</b>	<b>73</b>
	<b>APPENDIX A PROJECT PLANNING (PART 1)</b>	<b>77</b>
	<b>APPENDIX B PROJECT PLANNING (PART 2)</b>	<b>78</b>
	<b>APPENDIX C MODELING GEOMETRIES</b>	<b>79</b>

## LIST OF TABLES

	<b>PAGE</b>
Table 2.1 Advantages and disadvantages of fluidization (Gupta & Sathiyamoorthy, 1999)	10
Table 2.2 Drying of agro product in fluidized bed dryer	11
Table 2.3 Comparison between conventional fluidization bed and SFB	16
Table 2.4 The comparison of plenum chamber's type with details experimental	19
Table 2.5 RMSD for mean velocity distribution for tangential velocity	30
Table 3.1 Cases of parametric study on swirling fluidized bed distributor	39
Table 4.1 Scheme A meshing parameters	44
Table 4.2 Scheme B meshing parameters	44
Table 4.3 Scheme C meshing parameters	44
Table 4.4 Scheme D meshing parameters	45
Table 4.5 Grid sensitivity study summarization	45
Table 4.6 Analysis of variance for Mean Tangential Velocity	47
Table 4.7 Analysis of variance for Pressure Drop	49
Table 4.8 Static pressure data of 80° twist angle blade	53
Table 4.9 Static pressure data of 100° twist angle blade	53
Table 4.10 Static pressure data of 15° horizontal inclination blade (Nawi, 2013)	53
Table 4.11 Analysis of all the criteria	68

## LIST OF FIGURES

	<b>PAGE</b>
Figure 1.1 Swirling Fluidized Bed (SFB) with distributor (Nawi, 2013)	2
Figure 2.1 Schematic diagram of fluidization (Marimuthu, J., 2011)	7
Figure 2.2 Basic configuration of Swirling Fluidized Bed (Batcha et al., 2013)	13
Figure 2.3 Annular spiral distributor and the counter clockwise direction of the air flow (Ouyang & Levenspiel, 1986)	17
Figure 2.4 Configuration of blade SFB; (a) blade used to form annular and (b) blade angle and blade overlapping (Batcha & Raghavan, 2011)	20
Figure 2.5 CFD airflow simulation for modified chamber design cases; (a) Pre-distributor, (b) Ceramic balls packing and (c) Bottom plenum air inlet (Depypere et al., 2004)	26
Figure 2.6 Three-inlets chamber with a full-length cylindrical hub at the center; (a) Isometric view, (b) Top view and (c) Velocity distribution (Othman et al., 2008)	27
Figure 2.7 Velocity vector on the top plane (above) & bottom plane (bottom); (a) PIV and (b) CFD (Othman et al., 2009).	29
Figure 2.8 Comparing PIV, velocity magnitude results with various turbulence models for Swirling Fluidized Bed (Nawi, 2013)	30
Figure 3.1 Number of blade distributor; (a) 40, (b) 50 and (c) 60	34
Figure 3.2 Twist angle of blade distributor; (a) 80° and (b) 100°	35
Figure 3.3 Boundary type assigned to the geometries of SFB	36

Figure 3.4 Volume meshing and example of grid in the SFB; (a) Blade distributor and (b) Twist angle	37
Figure 4.1 Comparing of velocity magnitude deviation between schemes	43
Figure 4.2 Three dimensional graph of Mean Tangential Velocity	47
Figure 4.3 Interaction plot for Mean Tangential Velocity (TV); (a) Number of Blade (b) Twist angle	48
Figure 4.4 Three dimensional graph of Pressure Drop	50
Figure 4.5 Interaction plot for Pressure Drop (a) Number of blade (b) Twist angle	50
Figure 4.6 Fraction Open Area (FOA)	51
Figure 4.7 Measurement of pressure drop point in plenum chamber	52
Figure 4.8 Pressure drop comparison between current study and previous study by Nawi (2013).	54
Figure 4.9 Velocity magnitude at different twist angle; (a) 80° and (b) 100° via 40 blades distributor	56
Figure 4.10 Velocity magnitude at different twist angle; (a) 80° and (b) 100° via 50 blades distributor	56
Figure 4.11 Velocity magnitude at different twist angle; (a) 80° and (b) 100° via 60 blades distributor	57
Figure 4.12 Tangential velocity at different twist angle; (a) 80° and (b) 100° via 40 blades distributor	58
Figure 4.13 Tangential velocity at different twist angle; (a) 80° and (b) 100° via 50 blades distributor	58
Figure 4.14 Tangential velocity at different twist angle; (a) 80° and (b) 100° via 60 blades distributor	59

Figure 4.15 Radial velocity at different twist angle; (a) 80° and (b) 100° via 40 blades distributor	60
Figure 4.16 Radial velocity at different twist angle; (a) 80° and (b) 100° via 50 blades distributor	60
Figure 4.17 Radial velocity at different twist angle; (a) 80° and (b) 100° via 60 blades distributor	61
Figure 4.18 Axial velocity at different twist angle; (a) 80° and (b) 100° via 40 blades distributor	62
Figure 4.19 Axial velocity at different twist angle; (a) 80° and (b) 100° via 50 blades distributor	62
Figure 4.20 Axial velocity at different twist angle; (a) 80° and (b) 100° via 60 blades distributor	63
Figure 4.21 Analysis on high mean tangential velocity on 80° and 100° twist angle	65
Figure 4.22 Analysis on uniformity of tangential velocity distribution on 80° and 100° twist angle	66
Figure 4.23 Analysis on low pressure drop distribution on 80° and 100° twist angle	67

## LIST OF ABBREVIATIONS

A	Cross-Sectional Area of The Bed
AV	Axial Velocity
CFD	Computational Fluid Dynamics
$Q_{EAS}$	Equi-Angle Skewness
GAMBIT	Geometry and Mesh Building Intelligent Toolkit
PIV	Particle Image Velocimetry
PVC	Polyvinly Chloride
RANS	Reynolds Averaged Navier–Stokes
RV	Radial Velocity
SFB	Swirling Fluidized Bed
TV	Tangential Velocity
VM	Velocity Magnitude

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## LIST OF SYMBOLS

$(\Delta P)_{b,s}$	Bed Pressure Drop in Swirl Mode
$\epsilon$	Fractional Void Volume
$\Delta P$	Pressure Drop
$a_m$	Mean area (m <sup>2</sup> )
$Ar$	Archimedes number
$C_1$	Particle Shape Dependent
$C_2$	Species Dependent
$C_d$	Drag Coefficient
$d_p$	Particle Diameter
$D_p$	Effective Diameter of Particle
$\epsilon_M$	Porosity
$g$	Gravitation Acceleration
$G$	Mass Flow Rate of Fluid
$k$	Fraction of The Bed Weight Supported by Fluidized Gas
$L$	Height of Bed
$\dot{m}$	Mass Flow Rate (kg/s)
$m$	Mass of Particles
$M_b$	Mass of Bed
$P$	Pressure
$P_r$	Pressure Reference
$R$	Ratio of Distributor Pressure Drop to Bed Pressure Drop
$R_C$	Radius of Centre Conical Base
$Re_{mf}$	Reynold Number
$U_{mf}$	Minimum Fluidization Velocity
$v_c$	Centre Velocity
$v_r$	Radial Velocity
$v_z$	Axial Velocity
$v_\theta$	Tangential Velocity
$\theta$	Angle
$\mu_G$	Gas Viscosity
$\rho_G$	Gas Density
$\rho_p$	Particle Density
$v$	Free Stream Velocity
$\omega$	Angular Velocity (rad s <sup>-1</sup> )

## **Kesan Bilah Pongedar Bersudut Pih Terhadap Halaju Teragih Menggunakan Analisis Komputasi Untuk Lapisan Terbendalir Terpusar**

### **ABSTRAK**

Lapisan Terbendalir Terpusar (SFB) merupakan salah satu sistem terbendalir yang berpontensi dan diperkenalkan sebagai sistem yang menghasilkan interaksi cecair-pepejal. SFB digunakan secara meluas dalam proses seperti penjanaaan kuasa, industri kimia, pembuatan bahan dan pengeringan. Di dalam SFB, terdapat pongedar bilah yang berbentuk cecincin yang mana ia berfungsi untuk memberi prestasi terbaik dalam pembendaliran. Kecekapan di dalam sesebuah sistem pembendaliran bergantung kepada reka bentuk pongedar dan suntikan gas pada kecondongan. Kajian simulasi ini dijalankan dengan menggunakan perisian Dinamik Bendalir Berkomputeran (CFD) – GAMBIT 2.4.6 dan FLUENT 6.3.26 untuk mendapatkan keputusan pongedaran halaju dan susutan tekanan terhadap pelbagai reka bentuk pongedar bilah. Kajian ini menggunakan dua (2) jenis reka bentuk bilah pongedar bersudut pih. Sudut-sudut pih tersebut adalah  $80^\circ$  dan  $100^\circ$  dengan bilangan bilah pongedar adalah 40, 50 dan 60. Komponen utama halaju yang dianalisis di dalam sistem terbendalir adalah halaju tangen, halaju jejarian dan halaju paksi. Pembendaliran berlaku disebabkan oleh halaju paksi manakala kesan berputar adalah disebabkan oleh halaju tangen. Dalam kajian ini, halaju tangen merupakan komponen halaju utama kerana halaju tersebut mewakili halaju udara berputar di dalam sistem terbendalir. Daya empar dari gas berpusing menghasilkan halaju jejarian. Selain itu, prestasi susutan tekanan dan halaju seragam telah diukur dan dinilai. Keputusan dan penemuan terbaik daripada kajian simulasi ini adalah reka bentuk bilah pongedar bersudut pih memberi nilai terendah susutan tekanan berbanding dengan kajian terdahulu. Keseluruhan, reka bentuk bilah pongedar bersudut pih  $100^\circ$ , bilangan bilah pongedar 40 merupakan pongedar bilah yang terbaik berbanding yang lain.

## **Effect of Twist Blade Distributor on the Velocity Distribution using Computational Analysis for Swirling Fluidized Bed**

### **ABSTRACT**

Swirling Fluidized Bed (SFB) is one of the potential fluidized systems that has introduced a liquid-solid interaction system. SFB system is widely used in the power generation, chemical industry, material production and drying processes. Inside the SFB, there is ring-shaped annular blade distributor and it works is to give the best fluidization performance. The efficiency of a fluidized system depends on the distributor's design and the inclination of gas injection. The simulation study was conducted using Computational Fluid Dynamics (CFD) package GAMBIT 2.4.6 and FLUENT 6.3.26 software to obtain the result of velocity distribution and pressure drops on various blade distributor designs. This study uses two (2) twist angle blade distributor design types. The twist angles are  $80^\circ$  and  $100^\circ$  with the number of the blade distributor are 40, 50 and 60. The main component of the velocity analyzed in the fluidized system are tangential velocity, radial velocity and axial velocity. Fluidization is caused by axial velocity while the rotating effect causes by tangential velocity. In this study, tangential velocity is the main velocity component because the velocity represents the rotating air velocity in fluidized system. The centrifugal force of the spinning gas produces the radial velocity. Additionally, the performance of pressure drop and uniform velocity was measured and evaluated. The best results and findings of this simulation study are the design of the twist angle distributor gives the lowest value of pressure drop compared to previous studies. Overall, the design of the  $100^\circ$  twist angle and 40 blades distributor are the best distributors of blades compared to others.

## CHAPTER 1 : INTRODUCTION

### 1.1 Introduction

Fluidization which is known as a physiochemical phenomenon conveys the idea of transforming a fine solid bed into a fluid-like state by passing a gas. Gas flowing through an inlet exerts drag force on the particles and with the increase of gas flow the force exhibited may be large enough that it effects the arrangement of particles inside the bed (Paulose, 2006). Fluidized beds have been known to be used in a variety of applications namely in heat recovery, metal surface treatment, gasification, particle drying, oxidation, endothermic and exothermic, pallet coating, and etc (Paulose, 2006).

The Swirling Fluidized Bed (SFB) was developed to improve the performance of conventional fluidized beds. Unlike conventional fluidization, the gas enters the bed at a horizontal angle directed by a suitable distributor (Wellwood, 1997). In this case, the annular spiral distributor is used. The purpose of this study is to investigate the gas flow characteristics in the fluidized bed. A great understanding of this study is needed to improve the design of the airflow. Improved air flow design provides low pressure drop where optimum velocity distribution performance can be achieved.

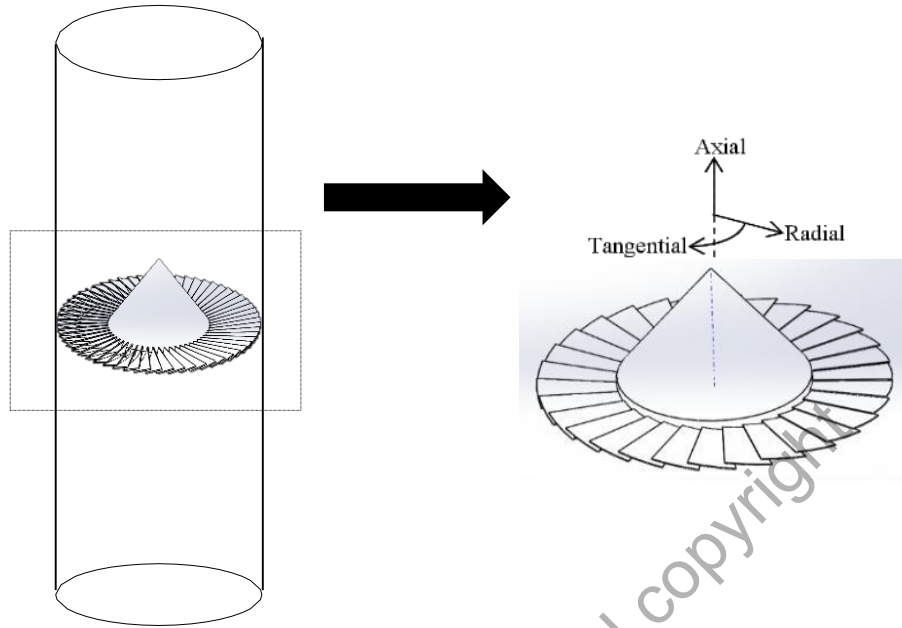


Figure 1.1 Swirling Fluidized Bed (SFB) with distributor (Nawi, 2013)

In this work, a Computational Fluid Dynamics (CFD) numerical analysis based on CFD package GAMBIT 2.4.6 and FLUENT 6.3.26 was utilized to investigate the velocity distribution and pressure drop influenced by the type of plenum chamber entry. The outcome from this study will improve the understanding of scale-up and erection of actual gas-solid contacting systems such as the drying of particles and combustors based on swirling flow principles.

## 1.2 Background of Study

The most important part in the SFB is the distributor that distributes air uniformly in the plenum chamber. Annular type of distributor with a number of blade is used in SFB. A good quality of fluidization is that it has low distributor pressure drop at the operating velocity in order to minimize the power consumption (Paulose, 2006). Influence of various design of distributors can lead to a better fluidization process quality.

Although fluidized beds are commercially available, minimal work has been done regarding their aerodynamic behaviour as this study is essential to improve the SFB system. Therefore, a detailed study regarding the SFB is necessary where analysis and investigation is needed to obtain optimum performance for the system.

### **1.3 Problem Statement**

Swirling Fluidized Bed is a new fluidized bed variant with an annular bed and inclined gas injection by a distributor (Raghavan, Kind & Martin, 2004). Although equipment operating with swirling principles is commercially available, there is little research on the basic aspects of air flow characteristics that has been published.

The improvement of SFB process can be done through a study of the parameter that can affect the distribution of air such as the number of blades, blade inclination angle, annular distributor width and bed aspect ratio such as height and diameter of the plenum chamber.

One of the main advantages of the SFB is that it possesses a low distributor pressure drop. In order to obtain an optimum performance for the SFB, the design of the distributor is important as it can affect the pressure drop value. A distributor consists two types of blade inclination angle which are horizontal and radial inclination angle. In the previous study, it is proved that distributor with  $15^\circ$  of horizontal inclination angle is the best design to provide a good performance of SFB (Nawi, 2013). But, this type of distributor takes a long time to create the tornado effect and this can be the weakness for SFB performance.

The design of distributor is being upgraded in order to produce a distributor that can produce a low pressure drop value and create a tornado effect in a short time. A research had been done by Batcha, Nawi, Sulaiman & Raghavan (2013) by inclining the distributor in a radially inward direction. The result of this research tells that distributor with  $13.5^\circ$  radial inclination angle give the shortest time for the creation of tornado. But, the pressure drop of this type of distributor is high. The success of this research can provide fresh and new information to learn more about this technology as SFB is used in many processes in the chemical industry. However, a good distributor design is still the main topic of discussion. In this research, a numerical study using CFD packages was applied caused by the highly complex nature of the flow.

#### **1.4 Objective**

The previous study on air flow characteristics focused on distributor using a certain number of blade with different horizontal and radial inclination as well as the aerodynamic characteristics in the plenum chamber. This research is an extension than the previous study in terms of the design. The objectives of this research are:

- i. To investigate the velocity distributions of tangential velocity, axial velocity and radial velocity by designing  $80^\circ$  and  $100^\circ$  twist angle blade distributor with the number of blades 40, 50 and 60.
- ii. To determine each of the pressure drop obtained from the simulation and investigate the effects of the axial entry of plenum chamber to the air

distribution using the number of blades distributor 40, 50 and 60 with 80° and 100° twist angle.

### **1.5 Scope of Study**

The scope of this study involves data extraction from the numerical simulations using commercial CFD package code FLUENT 6.3.26 to analyze flow distribution characteristics in a Swirling Fluidized Bed through various distributor configuration by designing 80° and 100° twist angle blade distributor with the number of blades 40, 50 and 60 via axial entry plenum chamber as inlet velocity irrespective of particle factors. The analysis of the SFB system performance based on uniformity of velocity magnitude; tangential velocity, axial velocity and radial velocity and low pressure drop distribution. This study was carried out grid sensitivity analysis to obtain the best new design distributors by comparing all result from the simulation.

### **1.6 Significance of Study**

The main outcome of this study is to identify the effect of axial entry on SFB air distribution for various distributor configurations. The results of this research will contribute to a better understanding of the mechanism of the SFB and the nature flow of the air distribution. The modifications and upgrade of the SFB design will result in optimal performance in terms of lower pressure drop which leads to a more uniformed air velocity through the configuration of the distributor. At the end of this study, this distributor configuration research is expected to produce a better SFB air flow distribution than before for the purposeful use of biomass in the worldwide industry.

## CHAPTER 2 : LITERATURE REVIEW

### 2.1 Fluidization

It often requires granular material to bring intimate contact with a fluid during various technological operations. The easiest way to do this is by fluidizing. Fluidization is a fundamental concept that has been applied in developing different types of fluidization beds that are currently being used for the industrial applications such as the swirling fluidized bed, vibro-fluidized bed, centrifugal fluidized bed, circulation of fluidized bed, tapered fluidized bed, magneto-fluidized bed, spouted fluidized bed and others. Fluidized bed systems are often used due to their high rates of heating and mixing: solid mixing and drying and thermochemical conversion as well as the cracking processes (Adanez et al., 2018; Li et al., 2018; Haron, Zakaria, & Batcha, 2017). However, limited work has been attempted to explore the link between the design of the distributor as well as the dynamics of the long-term bed.

Since the conventional fluidized bed has some certain limitations, it leads to further progress and enhanced development of the fluidized bed. The common feature shared between the mentioned fluidization beds is the basic concept on which these beds are based; although in certain aspects they differ from each other.

As the flow rate increases, the pressure drop throughout the bed also increases until at a specific flow rate where the frictional drag on the particles amounts to the same effective weight of the bed. During this state, the bed particles have similar properties to those of fluids hence it being referred to as a fluidized bed. The incipient fluidizing

velocity and incipient fluidization are respectively referred to as this condition and the corresponding velocity (Vanecek, Markvart, & Drbohlár, 1996).

Meanwhile, the point where suspended particles by liquid or gas flow direction, the force of friction between the particles of the liquid only counterbalances the weight of the particles, the vertical component of the force of compression between the adjacent particles that appear, and the lowering of pressure through any section of bed approximately equals the weight of the liquid and particles in that particular section, once the bed is said to be fluidized (Kunii & Levenspiel, 1990). According to Gupta and Sathiamoorthy (1999), fluidization may be a development of impartation of the fluid's properties to a bed of particles by passing the fluid through with a speed that brings the fastened bed to its most loosened attainable state simply before being remodelled it into a fluidized bed.

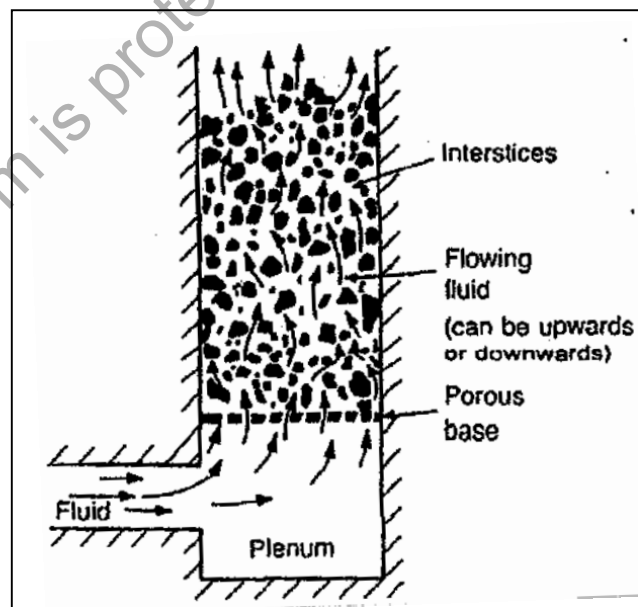


Figure 2.1 Schematic diagram of fluidization (Marimuthu, J., 2011)

In fluidized bed, the most important parameter is the minimum fluidization velocity,  $U_{mf}$ , which is the velocity of the fluidization starts. Lim, Zhu, & Grace (1995) states that the minimum fluidization velocity that needs to be applied is based on the required pressure drop to support a reduction buffer that acts on the particle at the fluidization minimum transfer point.

The minimum fluidization velocity,  $U_{mf}$ , is calculated using the Ergun's equation (Çengel & Cimbala, 2018) as mentioned in Equation (2.1), (2.2) and (2.3) as below;

$$\text{Re}_{mf} = \sqrt{C_1^2 + C_2 Ar} - C_1 \quad (2.1)$$

$$\text{Re}_{mf} = (\rho_G d_p U_{mf}) / \mu_G \quad (2.2)$$

$$Ar = (\rho_G \Delta p g d_p^3) / \mu_G^2 \quad (2.3)$$

Where;

$$\Delta p = (\rho_p - \rho_G)$$

$\rho_p$  - Particle density

$\rho_G$  - Gas density

$d_p$  - Particle diameter

$\mu_G$  - Gas

$U_{mf}$  - Minimum fluidization velocity

$C_1 C_2$  - Particle shape dependant and species dependant

$A_r$  - Archimedes number

$\text{Re}_{mf}$  - Reynolds number

Moreover, by using Ergun's equation in Equation (2.4) and (2.5) directly also can found the minimum fluidization velocity,  $U_{mf}$ , by substituting superficial fluid velocity with minimum fluidization velocity and the pressure drop across to the bed is equal to the effective weight per unit area of the particles at the point of incipient fluidization as per below;

$$\Delta P = (\rho_p - \rho_g)(1 - \varepsilon_M)gL \quad (2.4)$$

$$\frac{150\mu U_{mf}}{(D_p)^2} \frac{(1 - \varepsilon_M)}{(\varepsilon_M)^3} + \frac{1.75\rho g (U_{mf})^2}{D_p} \frac{1}{(\varepsilon_M)^3} = g(\rho_p - \rho_g) \quad (2.5)$$

Pattipati and Wen (1981) states temperature affects the minimum fluidization velocity. It decreases for small particles with increasing temperature. They also mentioned that viscous forces are dominant for small particles and at high temperatures. For larger particles, however, kinetic forces are dominant compared to viscous forces.

According to Vojtech, Miroslav, & Radek (1966), the particles within a fluidized bed are called bed particles. The fixed bed is a layer of particles that do not move relative to each other or relative to the container walls. On the other hand, under the action of gravity moving bed is a layer of particles moving as a whole. After the fluidization state has been reached, the bed volume is slightly larger than the fixed layer volume. The fluidized bed is said to be expanded accordingly. If the fluid's velocity increased, the bed will continue to expand where the bed height will also increase. However, the concentration of particles per bed volume unit decreases.

The main advantages and disadvantages of fluidized bed are tabulate in Table 2.1

below:

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

Advantages	Disadvantages
1. Due to good mixing, high heat transfer and high mass transfer under isothermal operation conditions can be achieved.	Without some special techniques, fine-sized particles cannot be fluidized and high conversion of a gaseous reactant in a single-stage reactor is difficult.
2. A fluid like behaviour facilitates the circulation between two adjacent reactors.	A fluidized bed's hydrodynamic features are complex, making it difficult to model and scale up.
3. There are no moving parts and it is not a mechanical agitated reactor; low maintenance cost.	Generation of turbulent mixing due to fines, gas or liquid jet interaction at the distributor and isolation because of a decision focusing undesirable products
4. Vertically installed and save space.	Fine elutriation and pumping energy consumption are inevitable
5. A continuous process and coupled with high throughput possible.	The bed would be defluidized by adhesive materials or reactions involving intermediate products of a sticky nature.
6. No need to train operator or skilled operator to operate the reactor.	It takes highly skilled professionals to design and scale up in this area.
7. Suitable for heat-sensitive or exothermic or endothermic reaction.	Limits on the operating velocity regime and particle size range selection.
8. In large scale operation, easy to handle and control	There may be severe erosion of immersed surfaces such as heat exchanger pipes.
9. Multistage operation was enabled by the time stay solid as well as liquid residence time can be adjusted to the desired level	In a fluidized bed reactor, reaction requiring a temperature gradient within the reactor cannot be accomplished.

## 2.2 Drying of Agro Product in Fluidized Bed

Many researchers reported that fluidized bed technology has been applied in the drying of wet solid particles successfully. The fluidized bed dryer performance studies are further elaborated and summarized in Table 2.2.

Table 2.2 Drying of agro product in fluidized bed dryer

Particles	Aim	Findings
Oil palm frond (Puspasari, Talib, Daud & Tasirin, 2012)	Investigation of drying kinetics in agitated fluidized bed dryer.	<ul style="list-style-type: none"> <li>- Agitation in the fluidized bed allowed the fibrous material to be fluidized and thus homogeneous mixing was achieved in the bed.</li> <li>- With the increase in drying temperature and surface air velocity, the drying rate increased but decreased with an increase in bed load.</li> <li>- Drying rate was severely affected by drying temperature, followed by air velocity, bed load and ultimately agitation velocity.</li> </ul>
Wheat grains (Özbey & Söylemez, 2005)	Present drying kinetics of wheat grain and the effects of the swirling flow field on the drying performance.	<ul style="list-style-type: none"> <li>- Removal of moisture, specific rate of removal of moisture and dryer efficiency by air mass flow rate, drying temperature and flow field properties.</li> <li>- Dry rates in fields of swirling flow are higher than in fields of non-swirling flow.</li> <li>- Thus, swirling motion increases the rate of drying, reducing drying time.</li> </ul>
Olive pomace (Meziane, 2011)	Investigate the effect of drying air temperature and bed height on olive pomace's drying kinetics in a fluidized bed dryer and fit the experimental data into	<ul style="list-style-type: none"> <li>- Olive pomace drying process occurred during the falling rate period.</li> <li>- Effective diffusivity values were calculated from 0.68 to <math>2.15 \times 10^{-7}</math> m<sup>2</sup>/s, increasing with sample temperature increase or bed height.</li> </ul>