Residence Time Distribution and Hydrodynamics Studies

of a Swirling Fluidized Bed

By

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Dissertation is submitted in partial fulfillment of

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the

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Approved by,

…………………………….
(Chin Yee Sing)

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

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CERTIFICATION OF ORIGINALITY

I hereby verify that this report was written by **KHOR JUN LI (12613)** and declare that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

…………………………..
(Khor Jun Li)

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ABSTRACT

Swirling fluidized bed has a lot of applications in various industries. Its ability to improve mass and heat transfer, causing vigorous mixing of particles is the main reason why it is preferred over other types of fluidized bed most of the time. Even so, the number of researches done is still little. There are still a lot of aspects in the swirling fluidized bed which are yet to be discovered. In this project, a brand new idea is implemented on the bed. It is regarding the installation of a spiral insert in the swirling fluidized bed and has never been done before. The purpose of installing the spiral insert is to increase the time spent by the particles in the reactor by forcing the particles to travel along the spiral channel before exiting the reactor. Besides, hydrodynamics study has been carried out to investigate the effect of using different types of longer twisted blades at the distributor. It is found that after minimum fluidization, the bed pressure drop of particles is lower when twisted blades are used at the distributor. However, there are several setbacks for using twisted blades.

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ABBREVIATION AND NOMENCLATURES

τ_m	Mean Residence Time
θ	Dimensionless Time
E(t)	Residence Time Distribution Function
$E(\theta)$	Residence Time in Dimensionless Form
M_{ii}	Amount of Particles Collected at Each Interval
A_o	Orifice plate area
C_d	Coefficient of discharge
ρ_{air}	Air density
β	Beta ratio
$V_{superficial}$	Superficial Velocity
ΔP	Pressure Drop
L/D	Length to Diameter ratio
SFB	Swirling Fluidized Bed
RTD	Residence Time Distribution
FOA	Fraction of Open Area
BR	Batch Reactor
PFR	Plug Flow Reactor
CSTR	Continuous Stirred-Tank Reactor

CHAPTER 1 : INTRODUCTION

1.1 Background of Study

Fluidization is a process where fluid is imparted on solid particles and forces them to suspend in the fluid. Fluidization occurs when the fluid pressure exerted on the particles is enough to overcome their weight. Fluidized bed was developed in the mid 20 century and since then it is used in wide variety of applications. It is used in commercial synthesis process of various chemical compounds like acrylonitrile, anile etc., polymerization of chemical compounds like ethylene and propylene, combustion of solid fuels, drying of fine particles and others [1]. A lot of researches and efforts have been done to improve the fluidized bed technology. Different types of fluidized beds have been introduced, for example, bubbling fluidized bed, circulating fluidized bed, annular fluidized bed, vibratory fluidized bed, swirling fluidized bed (SFB) and others. As compared to other types of fluidized beds, swirling fluidized bed is considered to be the latest technology. For conventional bed, the air which enters the bed through perforated plate distributor and it can be resolved into 3 components which are axial, radial and tangential components [2]. In a swirling fluidized bed, fluid is injected at an inclined angle and it consists of 2 components. The vertical component causes fluidization while the horizontal component causes the swirling motion [3]. The axial momentum transferred to the particle is minimized and larger fraction of momentum is transferred radially and tangentially in swirling fluidized bed. This results in vigorous mixing of particles, improving the heat and mass transfer and reducing the elutriation of particles [2]. As the vertical component is just a fraction of the fluid velocity, the velocity of the fluid entering the SFB can be increased to high values without the happening of elutriation [3]. Thus, the performance is greatly improved in swirling fluidized bed. Researches have been done to examine the behaviors of the bed under different circumstances, for example, bed with different shapes of particles, bed with different weights, multi-stage bed and so on.

1.2 Problem Statement

Although swirling fluidized bed has been in used for decades, at the moment, the use of an insert in the bed has never been tried before. The purpose of installing the spiral insert is to force the particles to travel along the spiral and thus spending more time in the bed. However, this is only a hypothesis and no experiments have been done before on this. The exact behavior of the bed with insert is determined from the experiment. On the other hand, hydrodynamics study of a swirling fluidized bed with long blades at the distributor is a relatively new field. Some researches have been done previously on that subject, but there are still certain aspects which are yet to be explored. Therefore, this project is aimed to further investigate the behavior of a SFB using different types of long blades at the distributor.

1.3 Objectives

There are two main objectives for this research. Firstly, it is aimed to determine the effect of installation of a spiral insert on the residence time distribution of a swirling fluidized bed. Secondly, it is aimed to study the hydrodynamic effect of using different types of long blades at the distributor. The following are the objectives of the project in detail:

i. To compare the effect of using two different types of spiral insert on the RTD of a swirling fluidized bed. The first spiral insert has one end touching the cylindrical wall whereas the same end does not touch the cylindrical wall for the second.

ii. To compare the hydrodynamic effects of using three different types of long blades at the distributor, which are straight blade, forward-twist-blade and backward-twist-blade.

iii. To compare the hydrodynamic effect of using spherical particles of different sizes on each type of blades.

iv. To compare the hydrodynamic effect of using particles with different shapes on each type of blades.

v. To compare the hydrodynamic effect of having different bed weights on each type of blades.

1.4 Scope of Study

For the RTD study of a swirling fluidized bed, only the effect of using different types of spiral insert is studied. The effect of using different types of particles and blades will not be covered due to the time constraint. As for the hydrodynamics study, the result would be mainly focused on the distributor pressure drop, bed pressure drop and different types of operation regimes. The velocity profile and motion trajectories of particles will not be studied in the project due to limited time.

CHAPTER 2 : LITERATURE REVIEW

Extensive studies have been done in the subject of swirling fluidized bed. The studies can be categorized into two main categories which are the hydrodynamics study and the residence time distribution study.

2.1 Hydrodynamics Study of SFB

In the hydrodynamics study of swirling fluidized bed, there are several aspects which the researches have focused on. They are bed pressure drop, distribution pressure drop and minimum fluidization velocity.

2.1.1 Bed Pressure Drop

There are numerous studies which have been done to study the bed pressure drop of a swirling fluidized bed under different conditions. One of the earliest studies was done by Sreenivasan and Raghavan who found out that the bed pressure drop for smaller particles in a packed regime is higher due to their larger viscous and kinetic energy losses. Besides, they have also discovered that the bed pressure drop of a SFB increases with the air flow rate which is different from a conventional fluidized bed. This is due to the increase in air velocity increases the wall friction caused by the centrifugal weight acting normal to the wall. The wall friction opposes the upward motion of the bed and causes higher bed pressure drop as it increases [3].

Mohideen et al. have made similar observation as Sreenivasan and Raghavan which is the bed pressure drop for smaller particles is higher. The explanation given by the authors is the surface area for smaller particles is actually higher as compared to large particles given the same amount of weight. Besides, the number of blades at the annular distributor is varied in the experiment conducted by the authors. The fraction of open area (FOA) is higher for smaller number of blades. The results obtained in the experiment show that the bed pressure drop due for smaller number of blades is higher due to larger momentum is transferred to the bed as the FOA increases. However, the effect of overlapping angle on the bed pressure drop was inconclusive based on the results and the authors suggested further investigations to be done in that aspect [2].

Similarly the study done by Marimuthu on the effect of overlapping angle on the bed pressure drop is inconclusive as well. There is no clear relationship between the two and it is very much depending on the shape of particles. Besides, the results obtain by the author show that the effect of particle shape on the bed pressure drop varies with bed weight and overlapping angle. The relationship between the particle shape and the bed pressure drop is not comprehensive. However, it is highlighted that the bed pressure drop for spherical particles is normally higher. This is due to higher energy needed to fluidize particles as the drag force across the spherical is lower. The drag force across the spherical particles is lower due to smooth flow across the surface [4].

The effect of bed weight on the bed pressure drop has been reported by Goo. It was found that as the bed weight increases, the bed pressure drop increases as well. This is because the bed height for higher bed loading is larger. Therefore, the air has to travel longer distance before it can escape the bed. This has caused bigger difference between the bed pressure before and after the bed [5].

2.1.2 Distributor Pressure Drop

The result of the experiment done by Paulose in 2006 shows that for a given superficial velocity, the distributor pressure drop is higher for distributor with smaller percentage area of opening. This is because the small opening area causes the air enters the distributor at high velocity, which in turn causes high pressure loss [6].

Besides, the distributor pressure drops for forward-twisted and backward-twisted blades are much smaller as compared to the straight blades. This is due to air exit the distributor at lower velocity which causes higher pressure. The lower velocity is caused by the twisted blades which vary the blade angle from inner to outer side of the distributor [7].

2.1.3 Minimum Fluidization Velocity

In the experiment conducted by Paulose, coffee beans and pepper were used and it is found that the minimum fluidization velocity for a vane type distributor is higher as compared to a perforated type distributor. Besides, the minimum fluidization velocity increases as the vane angle decreases [6]. Similarly, Mohideen et al. claim that the minimum fluidization velocity for SFB is lower as compared to the conventional fluidized bed. The potential energy needed for fluidization in SFB is only half of that of the CFB [2].

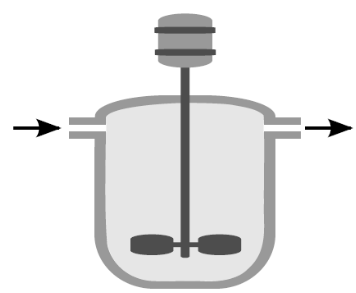
2.2 Residence Time Distribution of SFB

The residence time distribution is an important feature in a reactor as not all particles spend the same amount of time in the reactor. The amount of time spent by the particles in the reactor will determine the reaction time. The residence time distribution will determine the probability of different time spent by the particles in the reactor. In order to determine the residence time distribution, tracers have to be injected into the reactor and collected when they leave the reactor [8].

2.2.1 Ideal Reactor Models

Ideal reactors are devices which are designed to let chemical reactions take place under controlled condition to obtain specific desired products. There are 3 types of ideal reactor models which are batch reactor (BR), plug flow reactor (PFR) and continuous stirred-tank reactor (CSTR). Their main differences are listed in Table 2-1.

Table 2-1: Main Differences between Different Types of Ideal Reactor Models [9]

Batch Reactor	**Plug Flow Reactor**	**Continuous Stirred-Tank Reactor**
		
• Closed system • Discontinuous • Stirred	• Open system • Continuous • Non-stirred	• Open system • Continuous • Stirred

In an ideal PFR and BR, all the particles remain for the same time in the reactor. The time spent by the particles in a reactor can also be known as residence time. Residence time distribution can be affected by the mixing occurred in the reactor. In an ideal CSTR, all the particles are uniformly mixed while in an ideal PFR there is no axial mixing. Therefore, the residence time distribution for a CSTR and a PFR is different [10]. A swirling fluidized bed with particles feeding continuously into the bed and exit through an outlet ducting resembles a CSTR.

2.2.2 Theories of Residence Time Distribution

The residence time distribution can be represented by a function E(t) and it has the unit s^{-1}. E(t)dt provides information regarding the fraction of particles which left the reactor within a certain period of time, Δt. It can be defined as follows [11]:

$$\int_0^\infty E(t)dt = 1$$

The mean residence time, τ_m can be determined by the following formula [12]:

$$\tau_{m=} \int_0^\infty tE(t)dt$$

By having the value of the mean residence time, the variable t, can be made dimensionless by dividing every value of t by τ_m [12]. For example,

$$\theta = \frac{t}{\tau_m}$$

The purpose of using dimensionless time in the graph is to eliminate t as one of the adjustable parameter, so that set up with different reaction time which might be due to the size of setup and the scale of the reaction, can be compared using the same graph. Besides, the residence time distribution function in dimensionless form can be express as follows [12]:

$$E(\theta) = \tau_m E(t)$$

2.2.3 Residence Time Distribution Study of a Swirling Fluidized Bed

At the moment, there are very few references regarding the RTD study of a SFB. One of the studies which have been done is regarding how to improve the residence time of the SFB. According to Ashri, the RTD is found to be better in a multistage SFB due to numerous fluid-particle contacting and the solid product is more uniform [13]. Yudin on the other hand has studied the effect of bed weight and particle size on the RTD of Solids in a SFB. It was found out that by increasing the bed weight, the amount of time in which the particle resides in the bed will be increased. This is due to the increase in resistance to swirling motion. As for the effect of particle size however, it was found that the effect of increasing the particle size on the RTD is not significant [14].

CHAPTER 3 : METHODOLOGY

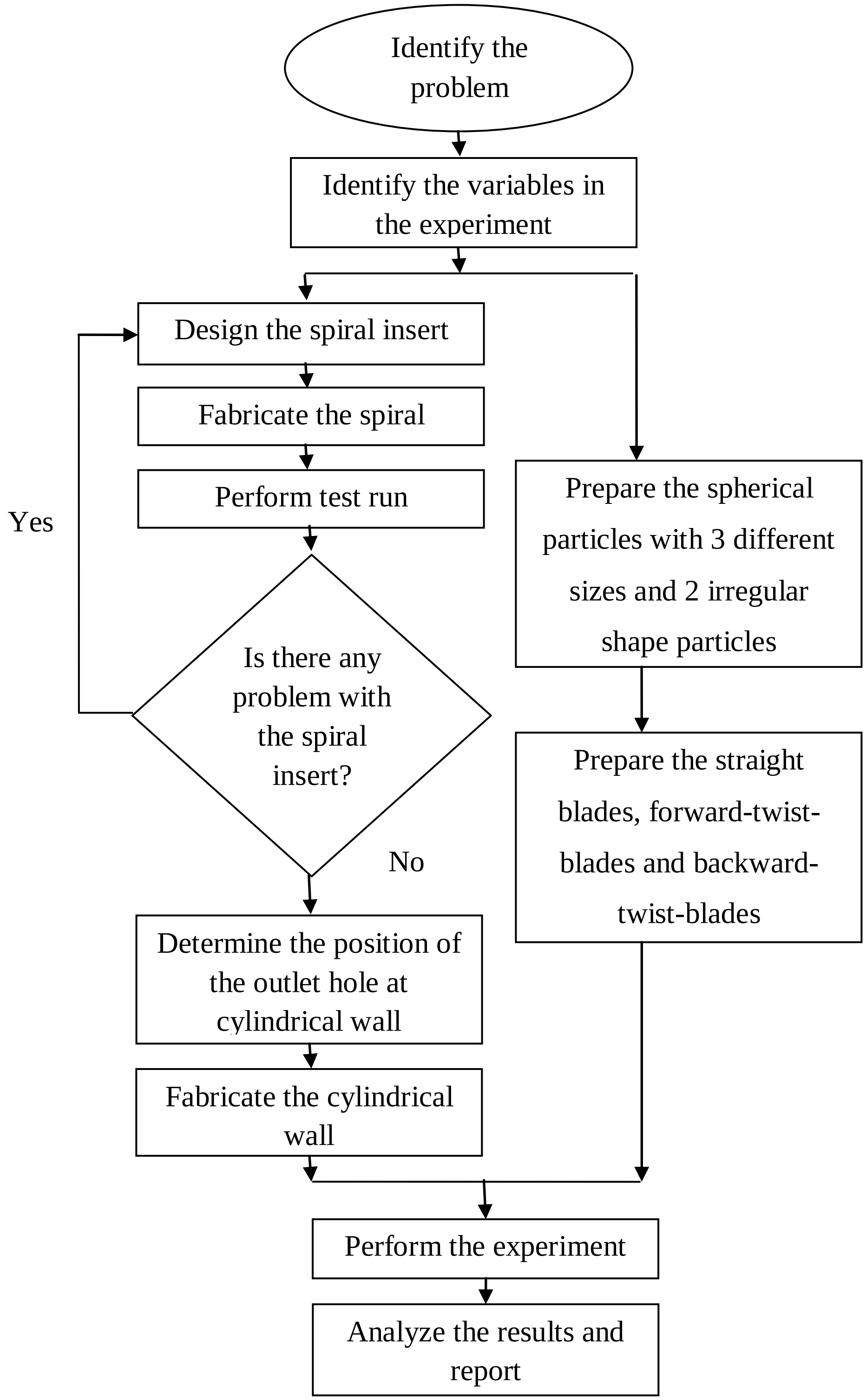


Figure 3-1: Flow Chart of the Final Year Project

3.1 Apparatus Set Up

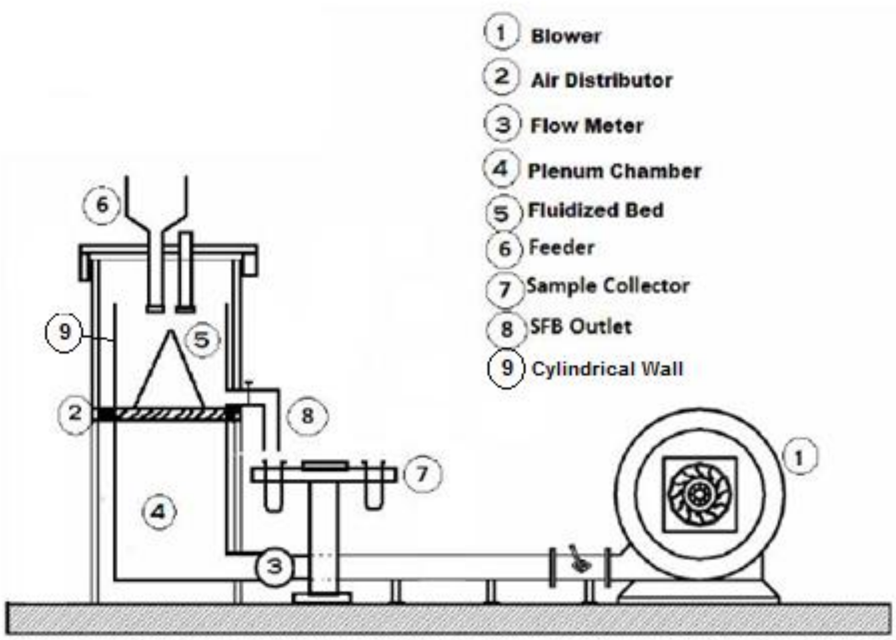


Figure 3-2: Schematic Diagram of the Apparatus, *reproduced from* [14]

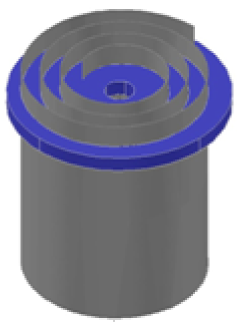
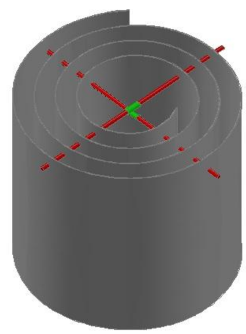
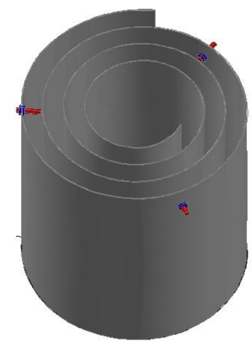
The blower forces the air to flow into the fluidized bed. Before the air enters the fluidized bed, it passes through a flow meter where the pressure drop across the flow meter is obtained and it is used to calculate the superficial velocity of the air. Then the air passes through the plenum chamber and the annular distributor before entering the bed. The inclination angles and overlap angles of the blades at the annular distributor can be varied by using different rings and blades respectively. The feeder is used to feed the bed particles into the bed during the experiment at a desired feed rate. The bed particles will escape from the outlet and drop into the sample collectors during the experiment.

3.2 Methodology for Residence Time Distribution Study

3.2.1 Design of the Spiral Insert

During the initial stage of the project, several designs of spiral insert have been proposed and considered. The designs are shown in Table 3-1.

Table 3-1: Proposed Designs of Spiral Insert

Design A	**Design B**	**Design C**
		
Description: A Perspex plate is used and a spiral shape channel is drilled on the Perspex. It is used guide the turning of a metal sheet. A hole is drilled in the middle of the plate so that the bed particles can be dropped from the feeder hopper into the fluidized bed.	**Description:** Holes are drilled on a metal sheet, metal rods are used to pass through the holes and female-female standoffs are used to allow the metal rods to be tightened from the inside.	**Description:** A metal sheet is turned and the stiffness of the metal sheet will allow the spiral shape to be fixed in position.Three holes which are 120^0 apart are drilled. Bolts are inserted into to the holes and tightened with nuts. The bolts will prevent movement of the standstill during the experiment.
Advantage: The gap of the spiral is consistent, it shape will not deformed during the experiment. It can be reused for many times.	**Advantage:** The shape of the spiral is fixed and can be quite consistent. Air can escape easily from the fluidized bed.	**Advantage:** Air can escape easily from the fluidized bed. The fabrication process is faster and drilling a lot of holes on the metal sheet is unnecessary and can be avoided.

Disadvantages: The air is trapped underneath the Perspex plate, only a little amount of air can escape. The hydrodynamic properties of the fluidized bed will be greatly affected. The fabrication process is tedious and it has to be done carefully as drilling holes or channel in the Perspex will causes it to crack or break.	**Disadvantages:** A lot of holes have to be drilled which can take a lot of time. The standoffs and metal rods connected at the centre may affect the flow of bed particles from feeding hopper into the bed.	**Disadvantages:** The shape of the spiral may be slightly deformed during the experiment. The gap of the spiral cannot be turned accurately.

In order to choose the best design, several important criteria for each design have been considered. The most important of all is that the spiral insert should allow the air to escape from the bed. Due to time constraint, the easiness in fabrication is one of important aspects as well. Besides, the gap width of the spiral should be as consistent as possible and it would be better if the spiral can be reused. Pugh concept selection matrix is used to choose the best design and is shown in the Table 3-2.

Table 3-2: Pugh Concept Selection Matrix

		Design A		Design B		Design C	
Criterion	**Weightage**	**Points (1-5)**	**Weighed Points**	**Points (1-5)**	**Weighed Points**	**Points (1-5)**	**Weighed Points**
Effect on the Hydrodynamics	40	1	40	5	200	5	200
Easiness in Fabrication	30	1	30	3	90	5	150
Reusability of the Insert	10	4	40	5	50	3	30
Consistency of the Gap Width	20	5	100	4	80	3	60
Total point	100		210		420		**440**

Based on the evaluation done in the Pugh Selection Matrix, design C is chosen.

3.2.2 Dimensions for Spiral Insert without Clearance with the Wall

The gap of the spiral insert is around 30mm and the end of the spiral touches the wall. The shape of the spiral can be approximately represented by the function $r(\alpha)=2.4\alpha+50$ where r is the radius from the centre while α is the angle. The number of turns for the spiral is 3. The height of the spiral is 280mm. The dimensions of the spiral are shown in Figure 3-3.

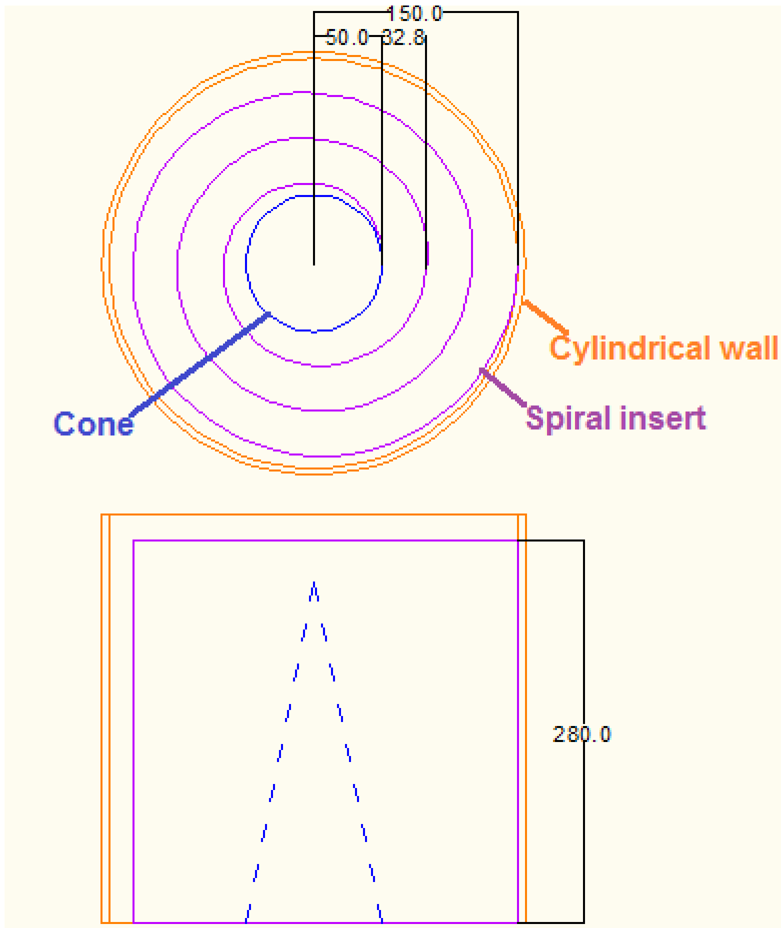


Figure 3-3: Dimensions of Spiral Insert with Wide Gap and Without Clearance with the Wall (in unit of mm)

3.2.3 Dimensions for Spiral Insert with Clearance with the Wall

Similarly, the gap of the spiral is around 30mm but the end of the spiral does not touch the wall. The number of turns for this spiral is 2.5. The gap between the end of the spiral and the cylindrical wall is around 17mm, which is enough for four 4mm particles to pass through. The dimensions of the spiral insert are listed in Figure 3-4.

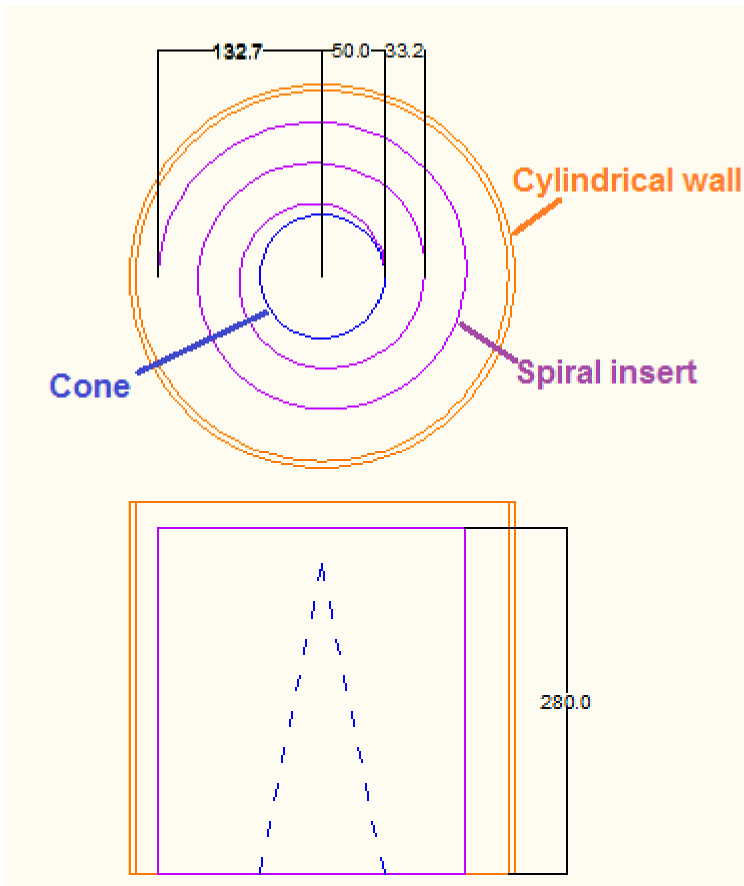


Figure 3-4: Dimensions of Spiral Insert with Wide Gap and with Clearance with the Wall (in unit of mm)

3.2.4 Fabrication of the Cylindrical Wall

The height of the outlet from the base, H, as shown in Figure 3-5 has to be determined before conducting the experiment. The outlet needed to be slightly above the swirling bed height of a given bed weight. During the experiment, as the SFB is filled with particles of the given bed weight, the particles will continue swirling within the SFB without exiting the bed when air is injected at minimum swirling velocity. The particles will only escape if there are new particles fed into the bed, and ideally, the rate of particles leaving the bed should be equal to the rate of particles entering the bed. Thus, the minimum swirling velocities and the swirling bed height of the particles have to be determined prior to outlet hole drilling on the cylindrical wall before conducting an experiment.

1kg of 4mm particles have been inserted into the SFB and the velocity of the inlet air is increased continuously until the particles are completely swirling. The swirling bed height of the particles at this point is 60mm. Thus, a hole is drilled on the Perspex wall at the height of 50mm from the base.

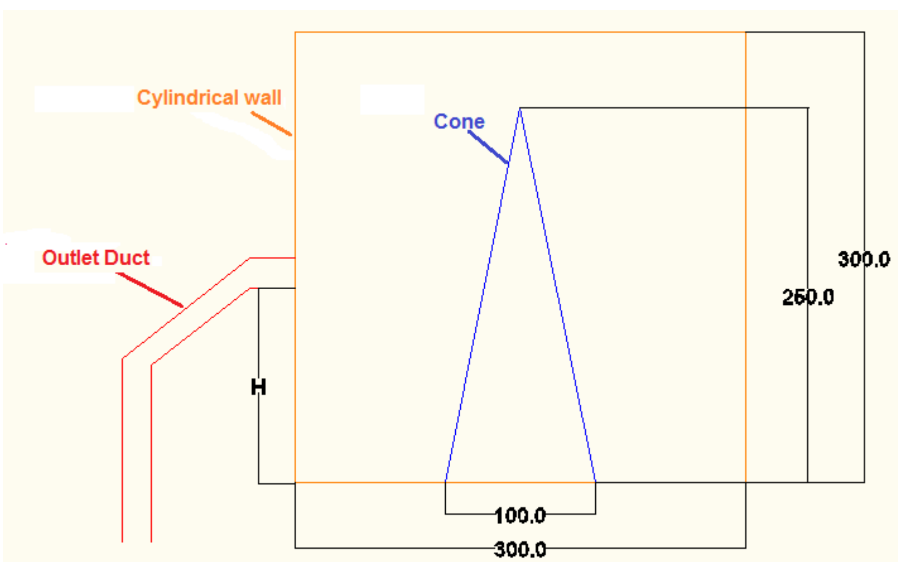
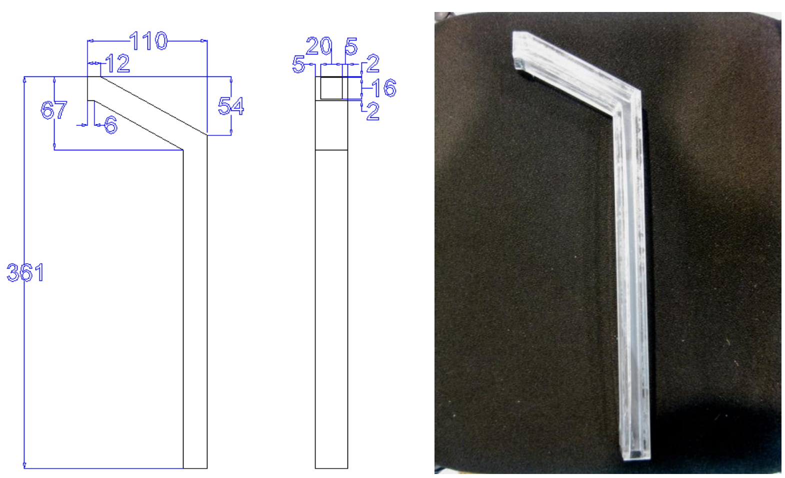


Figure 3-5: Important dimensions of SFB set up (in unit of mm)

Figure 3-6: Actual Cylindrical Wall with Outlet Ducting

3.2.5 Fabrication of the Outlet Ducting

After the height of the hole is ascertained, the dimensions of the outlet ducting can thus be determined. The outlet ducting is designed in such a way that the particles will fall off easily after the particles escape from the SFB. Therefore, there is a slanted portion after a short initial horizontal portion at the beginning of the ducting. The slanted portion should not touch the Perspex base of the set up, thus, the height of the hole has to be determined before the inclination angle can be decided.



(a) (b) (c)

Figure 3-7(a)-(c): Side View, Front View with Dimensions (in unit of mm) and Actual Outlet Ducting

3.2.6 Fabrication of the Spiral Insert

A piece of 0.3mm aluminum sheet is used initially for the spiral insert. Although it is easy to be fabricated due to its low stiffness, it was discovered that it does not stay in a fixed position firmly as it is very flexible. For that reason, a piece 0.5mm stainless steel sheet which has higher stiffness is tested to determine whether it is suitable to be used for spiral insert instead. Stainless steel sheet is able to stay in a firm position and it is far less flexible as compared to aluminum sheet, but because of its high stiffness, it is very difficult to be fabricated. The gap of the spiral insert cannot be consistent due to limitation of the fabrication tool and it is almost impossible to bend the sheet using bare hand. Thus, after considering the pros and cons of using aluminum sheet and stainless steel sheet, the final decision is to use the aluminum sheet which has been fabricated initially for spiral insert. However, to minimize errors which might occur during the experiment, the gap of the spiral insert has to be made consistent. In order to achieve that, combs will be used to slot in from the top of the spiral insert to hold the spiral insert in position.

(a) (b)

Figure 3-8(a)-(b): Spiral Insert (a) Spiraled from 0.3mm Aluminum Sheet (b) with Combs Fixing the Shape

3.2.7 RTD Experiment Procedure

i. 4mm particles of required weight are inserted into the feeder hopper.

ii. From the feeder hopper, the particles are fed continuously into the bed at a desired feed rate. Meanwhile, air is entering the bed at a desired flow rate as well.

iii. When the discharge rate of the particles into the bed is steady and the pressure differential across the orifice meter is consistent, tracers with a known weight are poured into the bed. The weight of the tracer particles are approximately 5% of the total bed weight. The tracers are similar to the bed particles, the only difference is the color.

iv. As the tracers are poured into the bed, a stopwatch is started simultaneously. The discharged bed particles are collected at a constant interval of time. The time interval applied in this experiment is 4 seconds.

v. The collection is continued until there is no tracer detected at the outlet. All the particles in the bed are collected and weighed to obtain the total bed weight.

vi. The tracers are separated from the bed particles. The weight of the tracers is measured using electronic weighing device.

The residence density function of the system is calculated using the formula,

$$E(t) = \frac{M_{ii}}{\Sigma M_{ii}}$$

where M_{ii} is the amount of tracers particles collected at each interval. The mean residence time of the SFB can be expressed in the following equation:

$$\bar{t} = \frac{\Sigma t_i M_{ii} \Delta t_i}{\Sigma M_{ii} \Delta t_i}$$

t_i is the measured clock time for the sample collecting. The dimensionless time and the respective residence time distribution can be calculated by using the following equations [13]:

$$\theta = \frac{t_i}{\bar{t}}$$

$$E(\theta) = \bar{t}E(t)$$

3.3 Methodology for Hydrodynamics Study

3.3.1 Experimental Conditions

The experiment conditions for the hydrodynamics study are summarized in Table 3-3.

Table 3-3: Experiment Conditions for Hydrodynamic Study

Experimental Conditions for Hydrodynamic Study	
Inclination Angle	15^{o}
Overlapping Angle	6^{o}
Forward Twist Angle	6^{o}
Backward Twist Angle	6^{o}
Spherical Particle Sizes	4mm, 5mm, 6mm
Irregular Shape Particles	Rice shape, Flat
Bed Weights	1kg, 2kg, 3kg

The weight and L to D ratio of each particle are listed in Table 3-4.

Table 3-4: Specifications of Particles Used in the Experiment

	Spherical, 6mm dia.	**Spherical, 5mm dia.**	**Spherical, 4mm dia.**	**Rice shape**	**Flat Shape**
					
L/D ratio	-	-	-	2	1.37
Weight (kg)	0.0976	0.0581	0.0245	0.0225	0.0156

3.3.1 Definition of Different Types of Twisted Blades

The identification of different types of twisted blades follows the definitions used by Warsita in his research [7]. Figure 3-9 illustrates the difference between different types of blades.

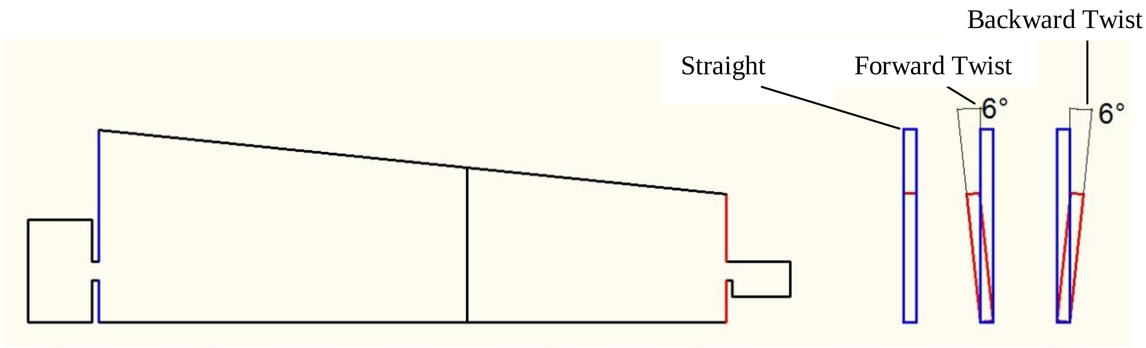


Figure 3-9: Illustration of Different Types of Long Blades

Figure 3-10 is extracted from Warsita's report [7], which shows the actual looks of the blades.

Figure 3-10: (From Left to Right) Straight Blade, Forward-Twist-Blade and Backward-Twist-Blade

3.3.2 Experiment Procedures

i. The selected types of blades are arranged and fitted on the 15^{o} stepped rings.
ii. A piece of Perspex is screwed on top of the inner stepped ring to keep the blades firmly in place.
iii. The centre cone is placed at the centre of the bed.
iv. The Perspex cylindrical wall and base are fastened to the plenum chamber using bolts and nuts.
v. The blower is switched on and the distributor pressure drops at different air flow rates are measured.
vi. The air flow rate is varied using electronic speed controller at the blower and it can be measured using an orifice flow meter.
vii. The bed is loaded with desired particles at desired weight.
viii. The total pressure drop across the bed and distributor for different air flow rate is measured.
ix. The bed pressure drop can be calculated by subtracting the distributor pressure drop from the total pressure drop across the bed and distributor.
x. The above steps are repeated using 3 different types of blades, 5 different types of particles at 3 different bed weights.

3.4 Calculation of Orifice Flow Meter

The superficial velocity of the inlet air can be calculated using the formulae below [7]:

Superficial Velocity, $V_{superficial} = \frac{Fluidizing\ air\ flow\ rate, Q}{Bed\ area, A_{bed}}$

The fluidizing air flow rate is found by

$$Q = A_o \times C_d \times \sqrt{\frac{2 \times g \times (\frac{\Delta P}{\rho_{air}})}{1 - \beta^4}}$$

Where,

Pipe diameter, D = 0.1m

Orifice diameter hole, d = 0.062m

A_o : Orifice plate area, $A_o = \frac{\pi \times d^2}{4} = \frac{\pi \times 0.062^2}{4} = 0.003019 m^2$

C_d : Coefficient of discharge, $C_D = 0.668$

ΔP : Pressure difference across orifice

ρ_{air} : Air density, $\rho_{air} = 1.2$ kg/m^3

β: Beta ratio, $\beta = \frac{d}{D} = \frac{0.062}{0.1} = 0.62$

On the other hand, the bed area can be found using the following formula,

$$A_{bed} = \frac{\pi}{4}({d_o}^2 - {d_i}^2)$$

$$A_{bed} = \frac{\pi}{4}(0.3^2 - 0.1^2) = 0.0628 m^2$$

Therefore, the superficial velocity can be simplified as,

$$V_{superficial} = \frac{0.003019 \times 0.668 \times \sqrt{2 \times 9.81 \times \frac{\Delta P}{1.2}}}{1 - 0.62^4} \times \frac{1}{0.0628}$$

$$V_{superficial} = 0.140656 \sqrt{Pressure\ drop\ across\ orifice, \Delta P}$$

CHAPTER 4 : RESULTS AND DISCUSSIONS

4.1 RTD Study of the Swirling Fluidized Bed

4.1.1 Spiral Insert with One End Touching the Cylindrical Wall

It is observed that the particles are clogged at the region near the end of the spiral. As the outlet is at a certain height from the base, particles which are swirling below the outlet cannot escape. Particles which are traveling at high speed towards that region face a strong resistance which prevents them from moving forward. The horizontal component of the velocity is cancelled out by the strong resistance while the vertical component of the velocity is still very great. Therefore, the particles elutriate at that region as illustrated in Figure 4-1. From the observation, it is concluded that this type of spiral insert is not suitable to be used in a swirling fluidized bed.

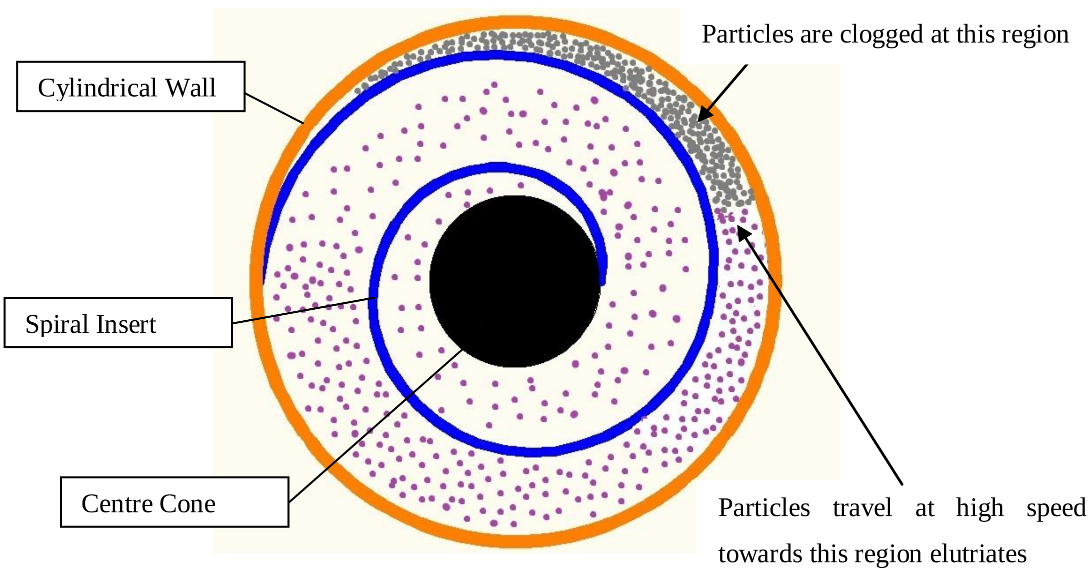


Figure 4-1: Observations from the Experiment which One End of Spiral is Touching the Cylindrical Wall

4.1.2 Spiral Insert with One End Not Touching the Cylindrical Wall

In this set up, the particles are not clogged as the end of the spiral insert is not blocking the swirling path of the particles. However, the particles are slowed down at the region near the end of the spiral insert. This is because at that region, the gap between the spiral insert and the wall is getting smaller and there are two streams of particles arriving at that region at the same time. The velocity of the particles at this region is much smaller as compared to velocity of the particles at other region. Particles which are travelling at high speed towards this region can still experience high resistance force which opposes their moving direction. Thus, similar to the previous case which the end of spiral insert touches the cylindrical wall, the particles elutriate at that region as shown in Figure 4-2. Therefore, this type of set up is not suitable to be used in a swirling fluidized bed as well.

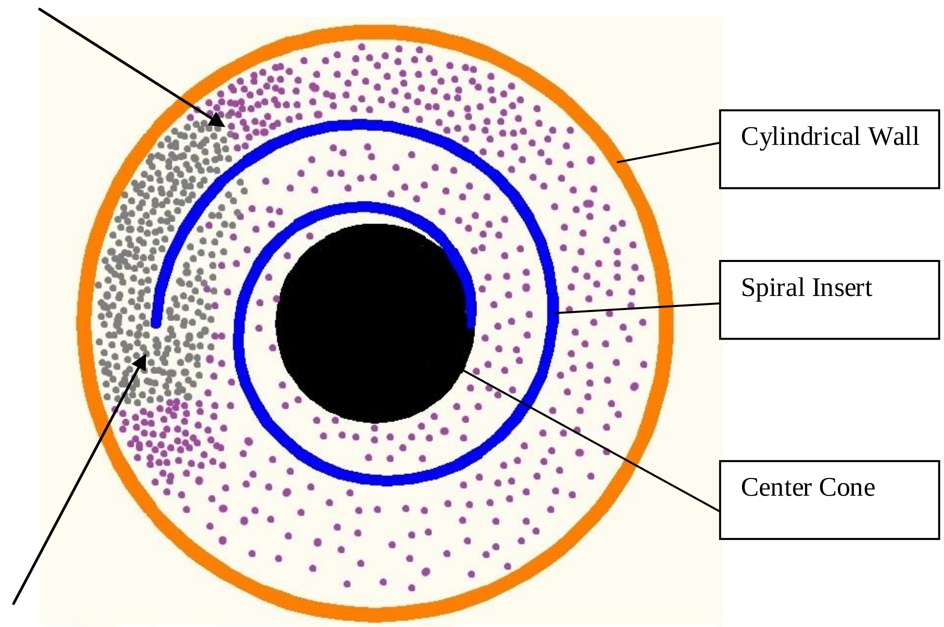
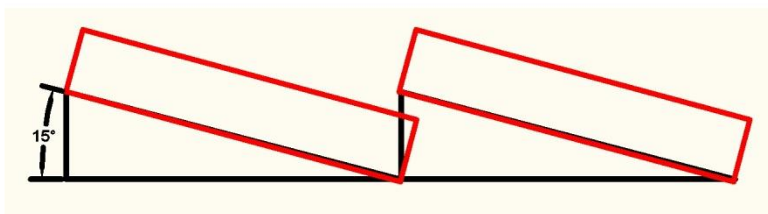


Figure 4-2: Observation from the Experiment which One End of Spiral Insert is not Touching the Wall

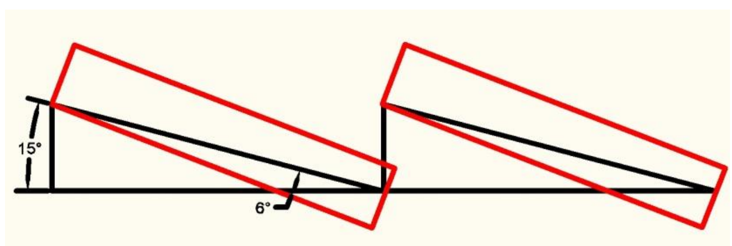
4.2 Hydrodynamics Study of the Swirling Fluidized Bed

4.2.1 Observations from Fixing Different Types of Blades at the Distributor

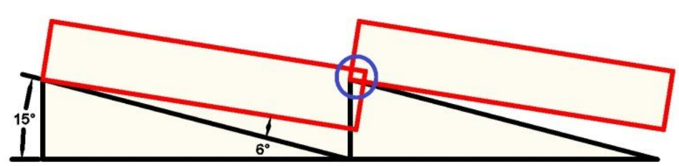
After 3 different types of blades are fixed at the distributor, it is noticed that the forward-twist-blades are not suitable to be used at the distributor. This is because a portion of the twisted blade overlaps with the subsequence blade at the inner ring of the distributor. The blades will stack on the previous blade and can never be fitted nicely at the inner ring. This problem did not occur when backward-twist-blades are fitted. It is illustrated in Figure 4-3. Thus, the experiment can only be conducted using 2 different types of blades at the distributor, which are straight blades and backward-twist-blades.



(a) Straight Blade



(b) Backward-Twist-Blade



(c) Forward-Twist-Blade

Figure 4-3(a)-(c): (a) Straight Blades (b) Backward-Twist-Blades (c) Forward-Twist-Blades at the Inner Ring

4.2.2 Distributor Pressure Drop

In this study, the term reference velocity had been used in place of superficial velocity that appeared in all literature referred to. The distributor pressure drop of distributor with different types of blades is measured. It is found that the distributor pressure drop of the backward-twist-blades is always lower than the straight blade for any reference velocity measured at the orifice. This is shown in Figure 4-4.

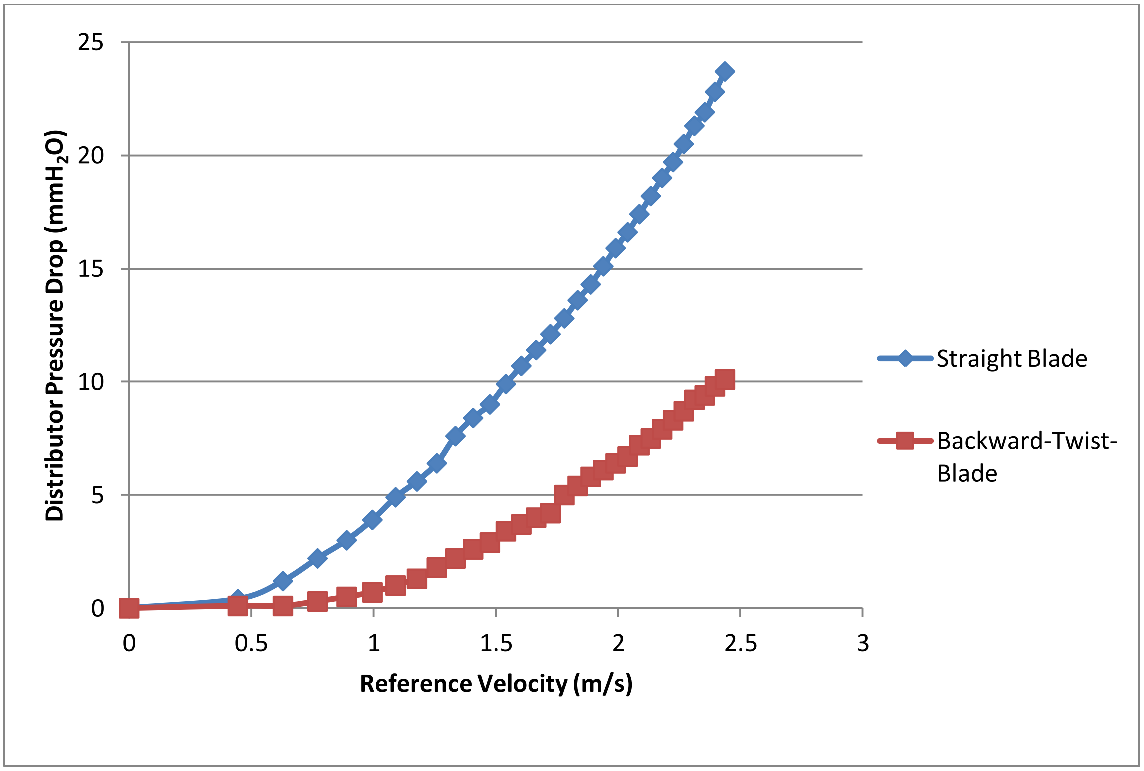


Figure 4-4: Distributor Pressure Drop for Different Types of Blades

The open area fraction at the distributor with a twisted blade is slightly larger as compared to the distributor with straight blade. From the continuity equation, assuming the air is incompressible, the velocity of the air which exits the distributor with twisted blade will thus be lower. According to Bernoulli's principle, higher pressure will be produced as the air velocity is decreased [15]. Therefore, the difference in pressure before and after the distributor will be smaller.

It is important to note that the reference velocity calculated using the formula shown in Section 3.4 is a function of pressure drop across orifice and bed area. It does not take into account the open fraction area of blades at the distributor. For this experiment, the open fraction area of twisted blades is higher than the straight blade. Therefore, the actual velocity of air exiting the twisted blade distributor is lower for the same magnitude of calculated reference velocity. All the graphs plotted in Chapter 4 will be based on calculated reference velocity as it will give a better comparison. As energy output required from the blower would be directly related to the calculated reference velocity, it will be easier to visualize the amount of energy required to achieve various operation regimes for different types of blades if the graphs are plot against calculated reference velocity.

4.2.3 Bed Pressure Drop for Different Bed Weight

The bed pressure drop for higher bed weight is found to be always larger. This kind of trend appears in all types of particles shapes, particle sizes and distributors. Figure 4-5 shows the bed pressure drop for 4mm particles with different bed weights using straight blades at the distributor.

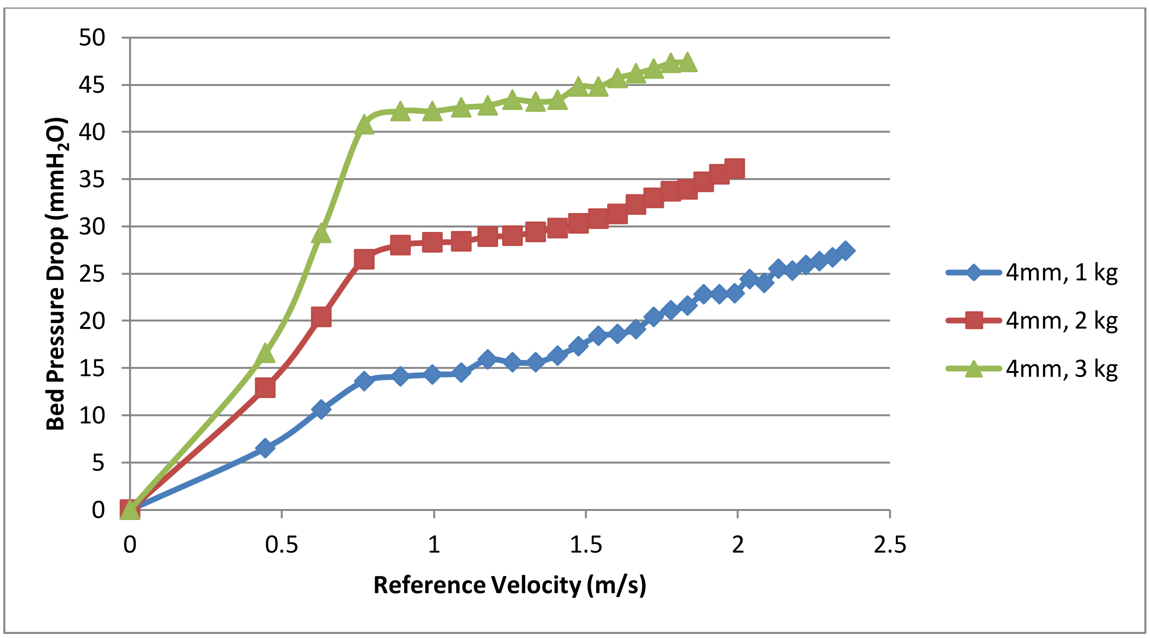


Figure 4-5: Bed Pressure Drop for Different Bed Weights

This is because for higher bed weight, higher bed height is observed due to larger number of particles inside the bed. Therefore, the air would be required to travel for longer distance before it can escape the bed. That is the reason why the difference between the bed pressure before and after the bed would be larger for higher bed weight.

Besides, from Figure 4-5, it is observed that the graph for higher bed weight ends at lower reference velocity. This is because at higher bed weight, the particles elutriate at lower reference velocity, the experiments are terminated once the particles start to fly away from the top of the cylindrical wall. This may due to the top surface of the bed of particles is closer to the top of the cylindrical wall as the bed height increases due to increase in bed weight. Thus, the particles can escape from the bed more easily for a same magnitude of force.

4.2.4 Bed Pressure Drop for Different Types of Blades at the Distributor

The major difference between the use of straight blades and twisted blades at the distributor is the trend of the bed pressure drop after the minimum fluidization velocity is achieved. From the results obtained, it is observed that the bed pressure drop for twisted blade distributor almost remains constant after minimum fluidization as contrary to the bed pressure drop for straight blade distributor which increases tremendously. The trend is shown in Figure 4-6.

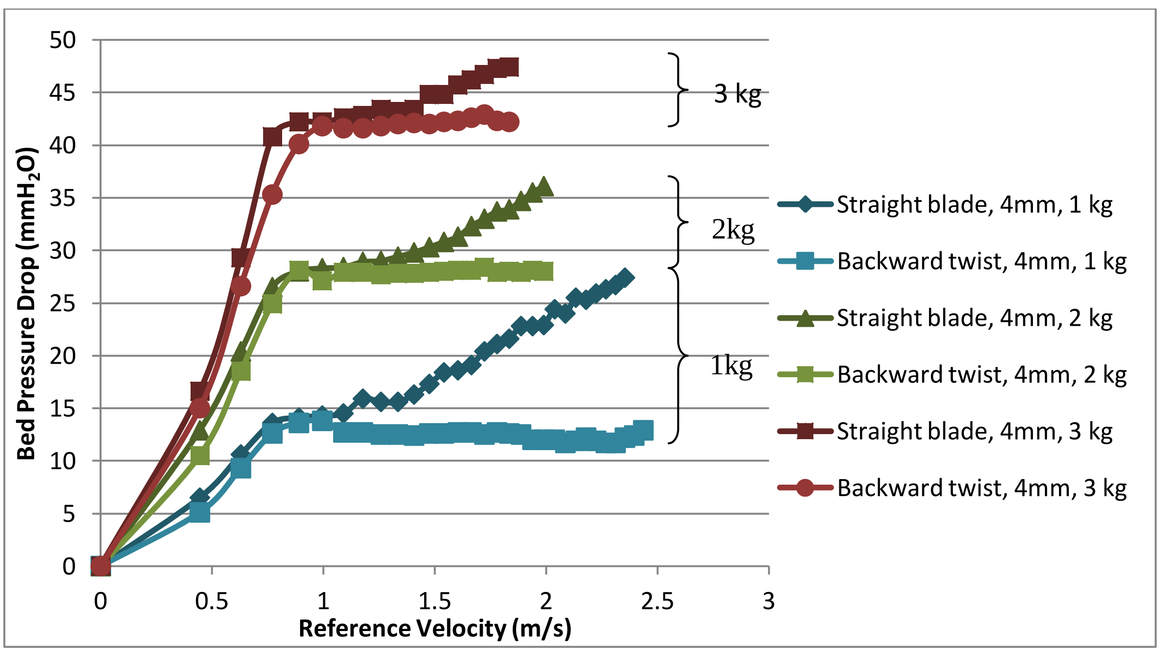


Figure 4-6: Comparisons of Bed Pressure Drops for Different Types of Distributors

Sreenivasan and Raghavan had explained that the bed pressure drop in a swirling fluidized bed is caused by the friction between the particles and the wall [3]. For twisted blade distributor, it is observed that the velocity of the particles which is close to the wall is not as high as those in straight blade distributor. Thus, the bed pressure drop of the twisted blade is observed to be lower. For straight blade distributor, as the reference velocity from the blower increases, the increase in velocity of the particles is much higher, therefore, the increase in bed pressure drop is greater.

4.2.5 Bed Pressure Drop for Spherical Particles with Different Sizes

Figure 4-7 and Figure 4-8 show the bed pressure drop for spherical particles with different sizes using different types of blades at the distributor.

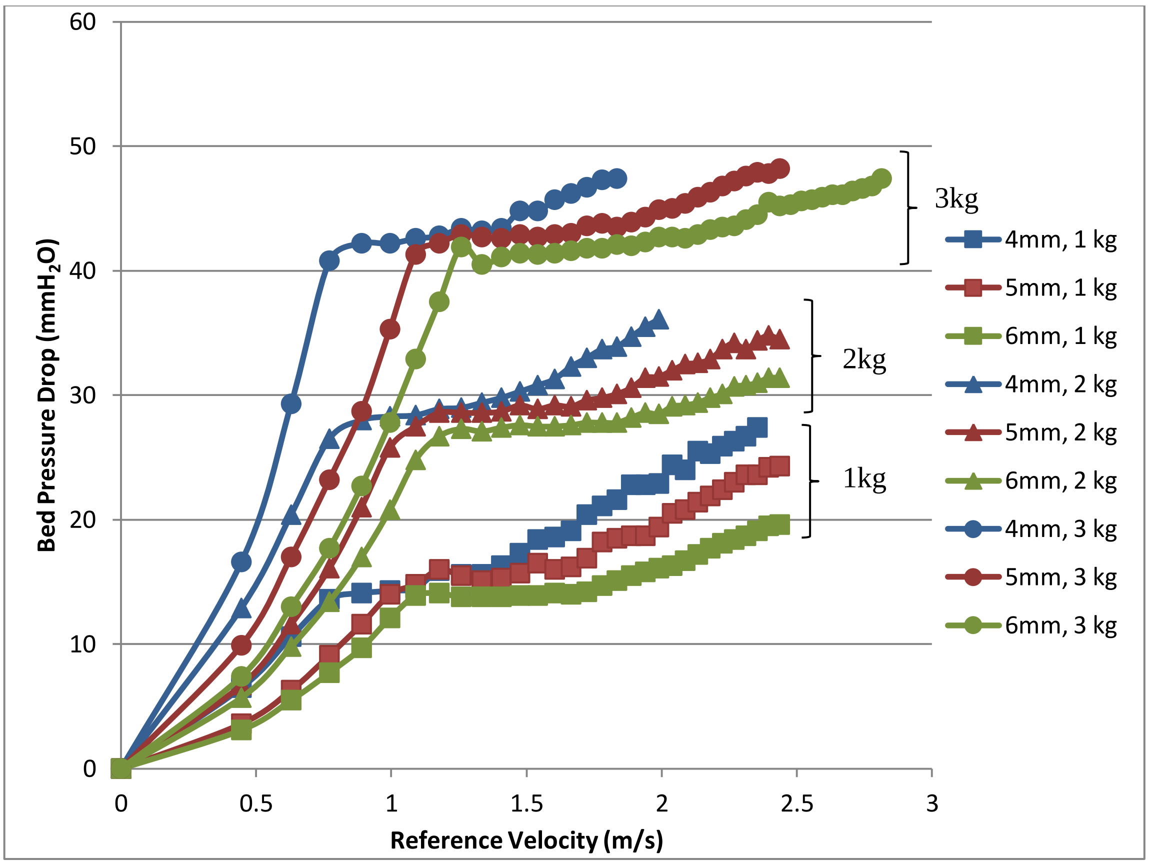


Figure 4-7: Bed Pressure Drops for Spherical Particles with Different Sizes Using Straight Blade Distributor

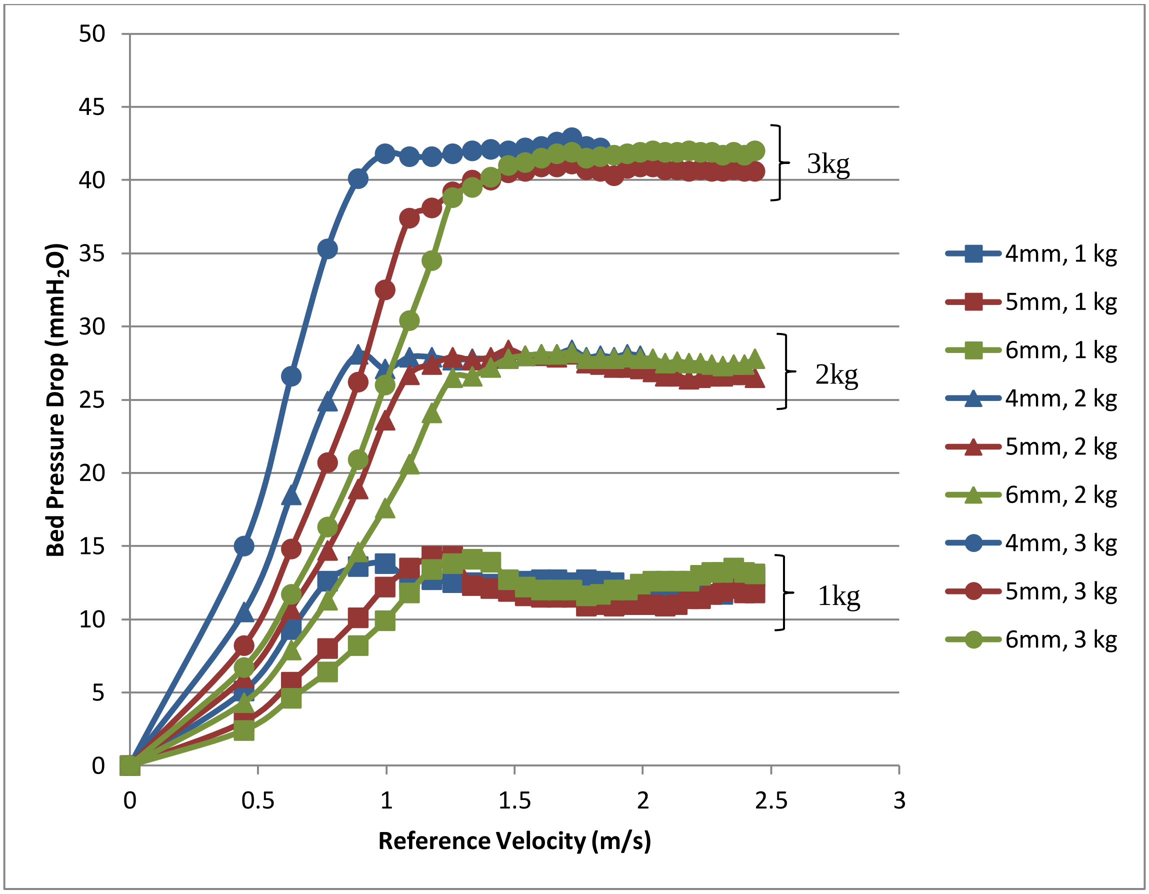


Figure 4-8: Bed Pressure Drop for Spherical Particles with Different Sizes Using Twisted Blade Distributor

It is discovered the bed pressure drop for smaller particles are usually larger due to higher surface for a similar amount of weight as what has been explained by Sreenivasan and Raghavan [3]. The friction between the smaller particles will be higher as the total surface area is larger. The higher friction is the factor which causes higher bed pressure drop.

Besides, it is interesting to note that for a twisted blade distributor, the bed pressure drop of spherical particles after the initial fluidization is almost similar regardless of the size. The factor that dictates the bed pressure drop after the initial fluidization is the bed weight.

4.2.6 Comparison of Bed Pressure Drop between Spherical Shape Particles and Rice Shape Particles

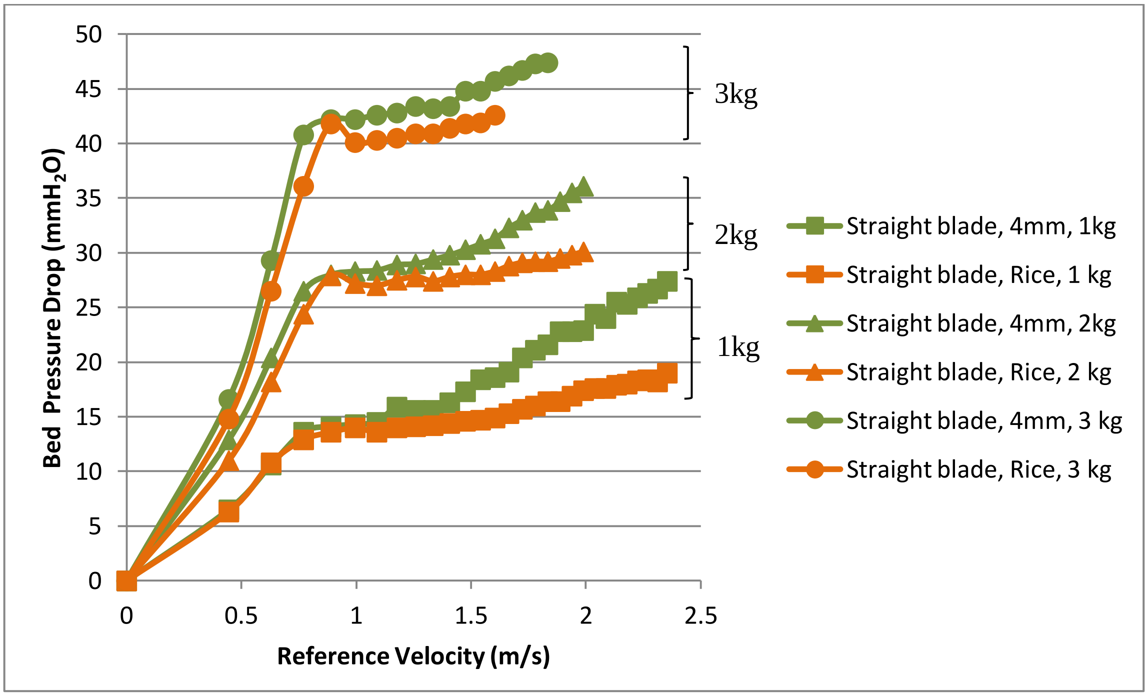


Figure 4-9: Bed Pressure Drop for 4mm Spherical and Rice Shape Particles for Straight Blade Distributor

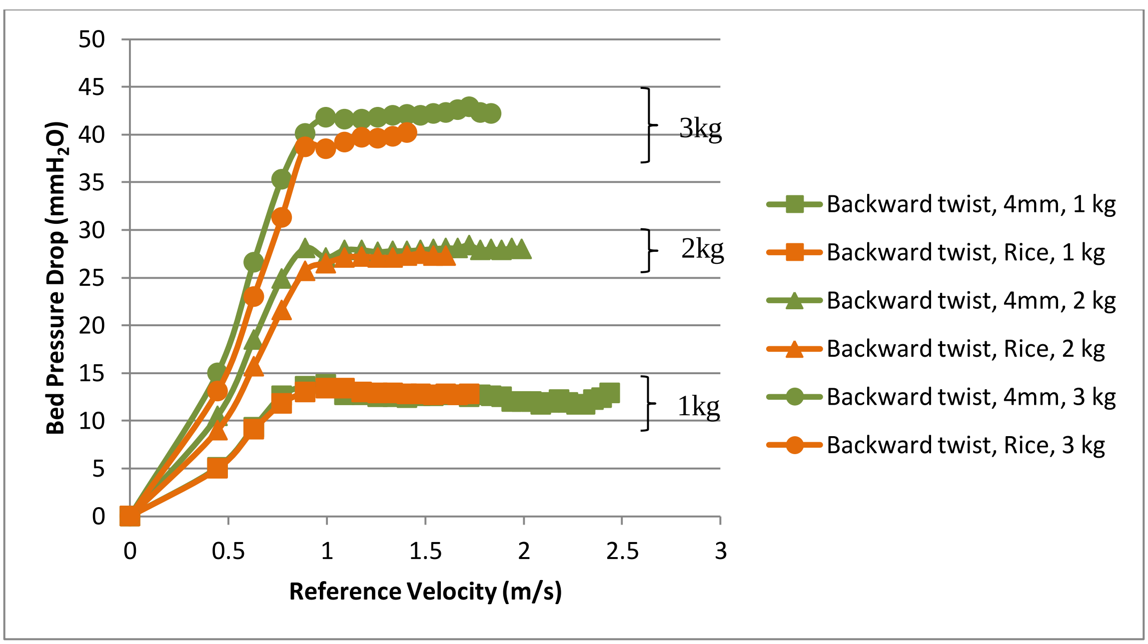


Figure 4-10: Bed Pressure Drop for 4mm Spherical and Rice Shape Particles for Twisted Blade Distributor

Figure 4-9 and Figure 4-10, it is obvious that the bed pressure drop for spherical particles is always higher than the rice shape particles, regardless of the bed weight or the type of blades used at the distributor. The comparison between the two types of particles should be quite accurate as both types of particles are having almost the same weight where their only difference is the shape. This may due to the rice particles tend to position themselves to facilitate the flow as explained by Goo [5].There is however, an error which may occur in the experiment as there are a lot of rice shapes particles adhere to the cylindrical wall due the electrostatic charge developed.

Besides, it is observed that the rice shape particles elutriates earlier as compared to the spherical particles. That is especially obvious for the twisted blade distributor. This may due to the larger surface area of the rice shape particles as compared to that of the spherical particles with similar weight which allow the air to exert higher drag force on the particles.

4.2.7 Various Operation Regimes before Swirling

From the experiment, it is observed that for all types of particles, swirling regime only occurs for bed which weighs 1 kg. For 2 kg and 3 kg beds, 2 layers with top bubbling and bottom swirling layers were observed. Figure 4-11 shows the pressure drop across the orifice required for various operation regimes before swirling occurs.

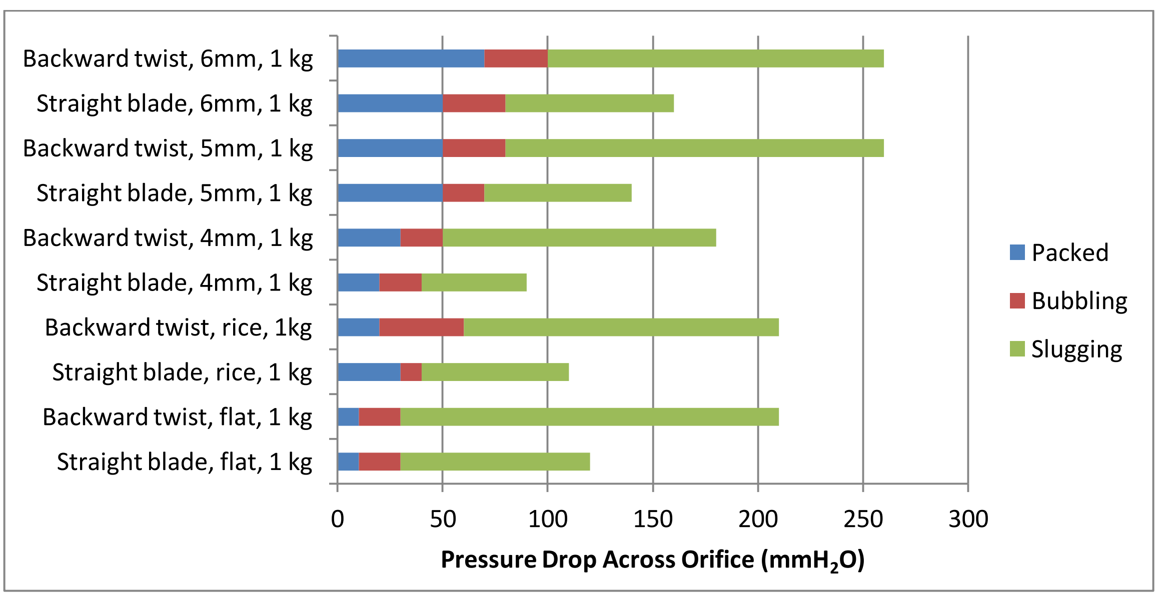


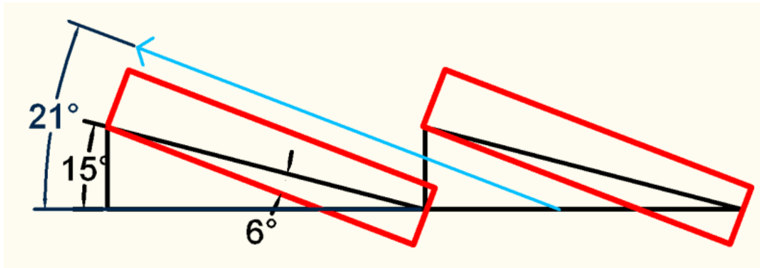
Figure 4-11: Various Operation Regimes before Swirling

From Figure 4-11, there are several conclusions which can be drawn. Firstly, for spherical particles, as the size of the particles increases, the pressure drop across orifice required to cause the bed start swirling increases. This may due to the increase in weight as the size of the particle increases which requires greater force to swirl the particles. Secondly, the required reference velocity of air from the blower to swirl the particles is always higher for twisted blade distributor as compared to straight blade distributor. This is because the velocity of air exiting the twisted blade distributor is lower for the same amount of pressure drop across the orifice. Therefore, the pressure drop across the orifice has to be higher in order to provide enough force for swirling. Besides, comparisons between 4mm spherical particles, rice particles and flat shape particles has shown that flat shape particles require highest reference velocity to start swirling while spherical particles require the least.

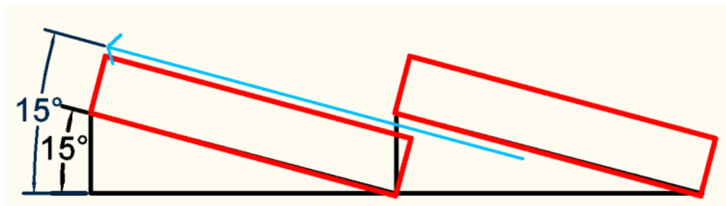
4.2.8 Observations during the Experiment

For straight blade distributor, it was observed that there is dead zone at the region near the cone where the particles do not move at the beginning. The dead zone becomes smaller and smaller as the reference velocity increases and finally eliminated. At higher reference velocity, the particles tend to mass towards the outer periphery, leaving a vacant region near the cone. On contrary, dead zone does not appear when backward-twist-blades are used at the distributor at the beginning.

Other than that, it is discovered that the particles in a SFB with twisted blade elutriates more easily. For 1 kg bed, the particles elutriate at very low superficial velocity where the particles are still at the slugging regime. For straight blade distributor, the air exits the distributor at the same angle throughout the length of the blade. This is not the case for backward twist blade distributor where the vertical component of the air velocity at the region near the cone is higher. Due to the increase in vertical component, the particles experience higher upward force which causes them to elutriate more easily. This is illustrated in Figure 4-12.



(a)



(b)

Figure 4-12 (a)-(b): The angle of exiting air at distributor (a) Straight Blades (b) Backward-Twist-Blades

CHAPTER 5 : CONCLUSION AND RECOMMENDATION

5.1 Conclusion

There are several conclusions which can be drawn from the experiments. Firstly, the idea of using a spiral insert to increase the residence time of a SFB is not feasible as the particles elutriate easily in the bed. As for the hydrodynamics study, there are several important breakthroughs in this research. Firstly, it is found that forward twist blade is not suitable to be used for the distributor with 15^o inclination angle as the blades stack on each other when they are fitted on the stepping rings. It is also discovered that for twisted blade distributor, the bed pressure drop of particles after minimum fluidization is lower. However, the particles would require larger air flow from the blower to start swirling and they tend to elutriate more easily if twisted blades are used at the distributor. Besides, for twisted blade distributor, it is found that the factor that dictates the bed pressure drop after the minimum fluidization is the bed weight as the effect of particles size on the bed pressure drop is insignificant after the minimum fluidization. By comparing the bed pressure drop of rice shape particles and spherical shape particles, it is found that the bed pressure drop for spherical particles is higher. This however should be further investigated and verified in the future as it is observed that there is huge amount of rice shape particles adhere to the cylindrical wall during the experiment which may affect the result. The disadvantage of using rice shape particles is they tend to elutriate more easily than the spherical shape particles. Besides, it is found that it is the easiest to swirl the spherical particles whereas flat shape particles are the hardest to be swirled.

5.2 Recommendation

There are still several aspects of SFB which can be further explored in the future:

i. Different ways to enhance the residence time of a SFB should be explored. For example inserting a smaller diameter cylindrical wall with a hole within the existing cylindrical wall may increase the residence time of particles in the bed.

ii. The effect of varying the twisted angle for the twisted blades should be studied in the future.

iii. To study the effect of particle shapes on the hydrodynamics of a SFB, the particles with different shapes should have similar density.

iv. The effect of particles sizes on the hydrodynamics of a SFB can be further studied using particles with different sizes but similar weight. It would justify whether it is the weight or the volume of particles that dominates the variation in bed pressure drop.

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APPENDICES

APPENDIX A: PROJECT GRANTT CHART

APPENDIX B: PARTIAL EXPERIMENT RAW DATA (HYDRODYNAMICS STUDY)

APPENDIX C: PROJECT RECOGNITION

APPENDIX A: PROJECT GRANTT CHART

No	Detail/Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	Key Milestone
1	Topic Selection		□													Topic selection (week 2)
2	Research study							□								Extended proposal submission (week 6)
3	Design the spiral insert															
4	Proposal defense									□						Proposal defense presentation (week 9)
5	Fabrication of the spiral insert											□				
6	Interim draft report submission													□		Interim report draft submission (week 13)
7	Interim report Submission														□	Interim report submission (week 14)

No	Detail/Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	Key Milestone
1	Fabrication of the cylindrical wall		□													Completion of the fabrication (week 2)
2	Fabrication of the outlet ducting							□								Completion of the fabrication (week 6)
3	Conducting the experiment															
4	Pre-SEDEX											□				Pre-SEDEX presentation (week 11)
5	Submission of draft report												□			Submission of draft (week 12)
6	Submission of dissertation													□		Submission of dissertation (week 13)
7	Oral presentation														□	Oral presentation (week 14)

Process

□ Key Milestone

APPENDIX B: PARTIAL EXPERIMENT RAW DATA (HYDRODYNAMICS)

Spherical, 4mm, 1 kg, Straight Blade					
ΔP across orifice (mmH_2O)	**ΔP across distributor (mmH_2O)**	**ΔP across distributor with particles (mmH_2O)**	**Reference velocity (m/s)**	**ΔP across bed (mmH_2O)**	**Observation**
0	0	0	0	0	Packed Bed
10	0.4	6.9	0.44479333	6.5	Packed Bed
20	1.2	11.8	0.62903275	10.6	Packed Bed
30	2.2	15.8	0.77040464	13.6	Bubbling
40	3	17.1	0.88958665	14.1	Bubbling
50	3.9	18.2	0.99458811	14.3	Slugging
60	4.9	19.4	1.08951669	14.5	Slugging
70	5.6	21.5	1.17681253	15.9	Slugging
80	6.4	22	1.25806551	15.6	Slugging
90	7.6	23.2	1.33437998	15.6	Slugging
100	8.4	24.7	1.40656	16.3	Swirling
110	9	26.3	1.47521257	17.3	Swirling
120	9.9	28.3	1.54080928	18.4	Swirling
130	10.7	29.3	1.60372515	18.6	Swirling
140	11.4	30.5	1.66426424	19.1	Swirling
150	12.1	32.5	1.72267715	20.4	Swirling
160	12.8	33.9	1.77917331	21.1	Swirling
170	13.6	35.2	1.83392987	21.6	Swirling
180	14.3	37.1	1.88709826	22.8	Swirling
190	15.1	37.9	1.93880916	22.8	Swirling
200	15.9	38.8	1.98917623	22.9	Swirling
Spherical, 4mm, 2 kg, Straight Blade					
ΔP across orifice (mmH_2O)	**ΔP across distributor (mmH_2O)**	**ΔP across distributor with particles (mmH_2O)**	**Reference velocity (m/s)**	**ΔP across bed (mmH_2O)**	**Observation**
0	0	0	0	0	Packed Bed
10	0.4	13.3	0.44479333	12.9	Packed Bed
20	1.2	21.6	0.62903275	20.4	Packed Bed
30	2.2	28.7	0.77040464	26.5	Bubbling
40	3	31	0.88958665	28	Bubbling
50	3.9	32.2	0.99458811	28.3	Bubbling
60	4.9	33.3	1.08951669	28.4	2 layers
70	5.6	34.5	1.17681253	28.9	2 layers
80	6.4	35.4	1.25806551	29	2 layers
90	7.6	37	1.33437998	29.4	2 layers
100	8.4	38.2	1.40656	29.8	2 layers
110	9	39.3	1.47521257	30.3	2 layers
120	9.9	40.7	1.54080928	30.8	2 layers
130	10.7	42	1.60372515	31.3	2 layers
140	11.4	43.7	1.66426424	32.3	2 layers
150	12.1	45.1	1.72267715	33	2 layers
160	12.8	46.5	1.77917331	33.7	2 layers
170	13.6	47.5	1.83392987	33.9	2 layers
180	14.3	49	1.88709826	34.7	2 layers
190	15.1	50.6	1.93880916	35.5	2 layers

Spherical, 4mm 3 kg, Straight Blade					
ΔP across orifice (mmH_2O)	**ΔP across distributor (mmH_2O)**	**ΔP across distributor with particles (mmH_2O)**	**Reference velocity (m/s)**	**ΔP across bed (mmH_2O)**	**Observation**
0	0	0	0	0	Packed Bed
10	0.4	17	0.44479333	16.6	Packed Bed
20	1.2	30.5	0.62903275	29.3	Packed Bed
30	2.2	43	0.77040464	40.8	Packed Bed
40	3	45.2	0.88958665	42.2	Bubbling
50	3.9	46.1	0.99458811	42.2	Bubbling
60	4.9	47.5	1.08951669	42.6	Bubbling
70	5.6	48.4	1.17681253	42.8	Bubbling
80	6.4	49.8	1.25806551	43.4	Bubbling
90	7.6	50.8	1.33437998	43.2	2 layers
100	8.4	51.8	1.40656	43.4	2 layers
110	9	53.8	1.47521257	44.8	2 layers
120	9.9	54.7	1.54080928	44.8	2 layers
130	10.7	56.4	1.60372515	45.7	2 layers
140	11.4	57.6	1.66426424	46.2	2 layers
150	12.1	58.8	1.72267715	46.7	2 layers
160	12.8	60.1	1.77917331	47.3	2 layers
170	13.6	61	1.83392987	47.4	Elutriation

Spherical, 5mm 1kg, Straight Blade					
ΔP across orifice (mmH_2O)	**ΔP across distributor (mmH_2O)**	**ΔP across distributor with particles (mmH_2O)**	**Reference velocity (m/s)**	**ΔP across bed (mmH_2O)**	**Observation**
0	0	0	0	0	Packed Bed
10	0.4	4	0.4447933	3.6	Packed Bed
20	1.2	7.5	0.6290328	6.3	Packed Bed
30	2.2	11.3	0.7704046	9.1	Packed Bed
40	3	14.6	0.8895867	11.6	Packed Bed
50	3.9	17.9	0.9945881	14	Packed Bed
60	4.9	19.7	1.0895167	14.8	Bubbling
70	5.6	21.6	1.1768125	16	Bubbling
80	6.4	21.9	1.2580655	15.5	Slugging
90	7.6	22.7	1.33438	15.1	Slugging
100	8.4	23.7	1.40656	15.3	Slugging
110	9	24.7	1.4752126	15.7	Slugging
120	9.9	26.4	1.5408093	16.5	Slugging
130	10.7	26.7	1.6037251	16	Slugging
140	11.4	27.6	1.6642642	16.2	Slugging
150	12.1	29	1.7226771	16.9	Swirling
160	12.8	31	1.7791733	18.2	Swirling
170	13.6	32.1	1.8339299	18.5	Swirling
180	14.3	33	1.8870983	18.7	Swirling
190	15.1	33.8	1.9388092	18.7	Swirling
200	15.9	35.3	1.9891762	19.4	Swirling

Spherical, 5mm 2 kg, Straight Blade					
ΔP across orifice (mmH_2O)	ΔP across distributor (mmH_2O)	ΔP across distributor with particles (mmH_2O)	Reference velocity (m/s)	ΔP across bed (mmH_2O)	Observation
0	0	0	0	0	Packed Bed
10	0.4	7.1	0.444793327	6.7	Packed Bed
20	1.2	12.8	0.629032755	11.6	Packed Bed
30	2.2	18.3	0.77040464	16.1	Packed Bed
40	3	24	0.889586653	21	Packed Bed
50	3.9	29.7	0.994588114	25.8	Packed Bed
60	4.9	32.4	1.089516691	27.5	Bubbling
70	5.6	34.2	1.176812527	28.6	Bubbling
80	6.4	35	1.25806551	28.6	Bubbling
90	7.6	36.2	1.33437998	28.6	Bubbling
100	8.4	37.1	1.40656	28.7	Bubbling
110	9	38.2	1.475212573	29.2	2 layers
120	9.9	38.8	1.540809281	28.9	2 layers
130	10.7	39.9	1.603725146	29.2	2 layers
140	11.4	40.5	1.664264236	29.1	2 layers
150	12.1	41.7	1.722677146	29.6	2 layers
160	12.8	42.6	1.779173306	29.8	2 layers
170	13.6	43.7	1.833929867	30.1	2 layers
180	14.3	44.9	1.887098265	30.6	2 layers
190	15.1	46.5	1.938809161	31.4	2 layers
200	15.9	47.4	1.989176228	31.5	2 layers

Spherical, 5mm 3 kg, Straight Blade					
ΔP across orifice (mmH_2O)	ΔP across distributor (mmH_2O)	ΔP across distributor with particles (mmH_2O)	Reference velocity (m/s)	ΔP across bed (mmH_2O)	Observation
0	0	0	0	0	Packed Bed
10	0.4	10.3	0.4447933	9.9	Packed Bed
20	1.2	18.2	0.6290328	17	Packed Bed
30	2.2	25.4	0.7704046	23.2	Packed Bed
40	3	31.7	0.8895867	28.7	Packed Bed
50	3.9	39.2	0.9945881	35.3	Packed Bed
60	4.9	46.2	1.0895167	41.3	Packed Bed
70	5.6	47.8	1.1768125	42.2	Bubbling
80	6.4	49.3	1.2580655	42.9	Bubbling
90	7.6	50.3	1.33438	42.7	Bubbling
100	8.4	51	1.40656	42.6	Bubbling
110	9	51.9	1.4752126	42.9	Bubbling
120	9.9	52.6	1.5408093	42.7	Bubbling
130	10.7	53.6	1.6037251	42.9	Bubbling
140	11.4	54.4	1.6642642	43	Bubbling
150	12.1	55.7	1.7226771	43.6	2 layers
160	12.8	56.6	1.7791733	43.8	2 layers
170	13.6	57.1	1.8339299	43.5	2 layers
180	14.3	58.2	1.8870983	43.9	2 layers
190	15.1	59.4	1.9388092	44.3	2 layers
200	15.9	60.8	1.9891762	44.9	2 layers

Spherical, 6mm 1 kg, Straight Blade					
ΔP across orifice (mmH_2O)	**ΔP across distributor (mmH_2O)**	**ΔP across distributor with particles (mmH_2O)**	**Reference velocity (m/s)**	**ΔP across bed (mmH_2O)**	**Observation**
0	0	0	0	0	Packed Bed
10	0.4	3.5	0.44479	3.1	Packed Bed
20	1.2	6.7	0.62903	5.5	Packed Bed
30	2.2	9.9	0.7704	7.7	Packed Bed
40	3	12.7	0.88959	9.7	Packed Bed
50	3.9	16	0.99459	12.1	Packed Bed
60	4.9	18.8	1.08952	13.9	Bubbling
70	5.6	19.7	1.17681	14.1	Bubbling
80	6.4	20.2	1.25807	13.8	Bubbling
90	7.6	21.4	1.33438	13.8	Slugging
100	8.4	22.2	1.40656	13.8	Slugging
110	9	22.9	1.47521	13.9	Slugging
120	9.9	23.8	1.54081	13.9	Slugging
130	10.7	24.8	1.60373	14.1	Slugging
140	11.4	25.4	1.66426	14	Slugging
150	12.1	26.3	1.72268	14.2	Slugging
160	12.8	27.5	1.77917	14.7	Slugging
170	13.6	28.7	1.83393	15.1	Swirling
180	14.3	29.8	1.8871	15.5	Swirling
190	15.1	30.9	1.93881	15.8	Swirling
200	15.9	32	1.98918	16.1	Swirling

Spherical, 6mm 2 kg, Straight Blade					
ΔP across orifice (mmH_2O)	**ΔP across distributor (mmH_2O)**	**ΔP across distributor with particles (mmH_2O)**	**Reference velocity (m/s)**	**ΔP across bed (mmH_2O)**	**Observation**
0	0	0	0	0	Packed Bed
10	0.4	6.1	0.44479	5.7	Packed Bed
20	1.2	11	0.62903	9.8	Packed Bed
30	2.2	15.6	0.7704	13.4	Packed Bed
40	3	20	0.88959	17	Packed Bed
50	3.9	24.7	0.99459	20.8	Packed Bed
60	4.9	29.7	1.08952	24.8	Packed Bed
70	5.6	32.3	1.17681	26.7	Bubbling
80	6.4	33.7	1.25807	27.3	Bubbling
90	7.6	34.7	1.33438	27.1	Bubbling
100	8.4	35.8	1.40656	27.4	Bubbling
110	9	36.6	1.47521	27.6	Bubbling
120	9.9	37.4	1.54081	27.5	2 layers
130	10.7	38.2	1.60373	27.5	2 layers
140	11.4	39	1.66426	27.6	2 layers
150	12.1	39.9	1.72268	27.8	2 layers
160	12.8	40.6	1.77917	27.8	2 layers
170	13.6	41.4	1.83393	27.8	2 layers
180	14.3	42.5	1.8871	28.2	2 layers
190	15.1	43.7	1.93881	28.6	2 layers
200	15.9	44.4	1.98918	28.5	2 layers

Spherical, 6mm 3 kg, Straight Blade					
ΔP across orifice (mmH_2O)	**ΔP across distributor (mmH_2O)**	**ΔP across distributor with particles (mmH_2O)**	**Reference velocity (m/s)**	**ΔP across bed (mmH_2O)**	**Observation**
0	0	0	0	0	Packed Bed
10	0.4	7.8	0.44479	7.4	Packed Bed
20	1.2	14.2	0.62903	13	Packed Bed
30	2.2	19.9	0.7704	17.7	Packed Bed
40	3	25.7	0.88959	22.7	Packed Bed
50	3.9	31.7	0.99459	27.8	Packed Bed
60	4.9	37.8	1.08952	32.9	Packed Bed
70	5.6	43.1	1.17681	37.5	Packed Bed
80	6.4	48.3	1.25807	41.9	Packed Bed
90	7.6	48.1	1.33438	40.5	Bubbling
100	8.4	49.5	1.40656	41.1	Bubbling
110	9	50.4	1.47521	41.4	Bubbling
120	9.9	51.2	1.54081	41.3	Bubbling
130	10.7	52.1	1.60373	41.4	Bubbling
140	11.4	53	1.66426	41.6	2 layers
150	12.1	53.9	1.72268	41.8	2 layers
160	12.8	54.6	1.77917	41.8	2 layers
170	13.6	55.7	1.83393	42.1	2 layers
180	14.3	56.3	1.8871	42	2 layers
190	15.1	57.4	1.93881	42.3	2 layers
200	15.9	58.6	1.98918	42.7	2 layers

Rice Shape, 1 kg, Straight Blade					
ΔP across orifice (mmH_2O)	**ΔP across distributor (mmH_2O)**	**ΔP across distributor with particles (mmH_2O)**	**Reference velocity (m/s)**	**ΔP across bed (mmH_2O)**	**Observation**
0	0	0	0	0	Packed Bed
10	0.4	6.7	0.44479	6.3	Packed Bed
20	1.2	12	0.62903	10.8	Packed Bed
30	2.2	15.1	0.7704	12.9	Packed Bed
40	3	16.6	0.88959	13.6	Bubbling
50	3.9	17.9	0.99459	14	Slugging
60	4.9	18.5	1.08952	13.6	Slugging
70	5.6	19.6	1.17681	14	Slugging
80	6.4	20.5	1.25807	14.1	Slugging
90	7.6	21.8	1.33438	14.2	Slugging
100	8.4	22.8	1.40656	14.4	Slugging
110	9	23.6	1.47521	14.6	Slugging
120	9.9	24.6	1.54081	14.7	Swirling
130	10.7	25.6	1.60373	14.9	Swirling
140	11.4	26.7	1.66426	15.3	Swirling
150	12.1	27.8	1.72268	15.7	Swirling
160	12.8	28.8	1.77917	16	Swirling
170	13.6	30	1.83393	16.4	Swirling
180	14.3	30.7	1.8871	16.4	Swirling
190	15.1	32	1.93881	16.9	Swirling
200	15.9	33.3	1.98918	17.4	Swirling

Rice Shape 2 kg, Straight Blade					
ΔP across orifice (mmH_2O)	**ΔP across distributor (mmH_2O)**	**ΔP across distributor with particles (mmH_2O)**	**Reference velocity (m/s)**	**ΔP across bed (mmH_2O)**	**Observation**
0	0	0	0	0	Packed Bed
10	0.4	11.4	0.44479	11	Packed Bed
20	1.2	19.4	0.62903	18.2	Packed Bed
30	2.2	26.6	0.7704	24.4	Packed Bed
40	3	30.9	0.88959	27.9	Packed Bed
50	3.9	31.1	0.99459	27.2	Bubbling
60	4.9	31.9	1.08952	27	Bubbling
70	5.6	33.1	1.17681	27.5	Bubbling
80	6.4	34.2	1.25807	27.8	Bubbling
90	7.6	35	1.33438	27.4	Bubbling
100	8.4	36.2	1.40656	27.8	2 layers
110	9	37	1.47521	28	2 layers
120	9.9	37.9	1.54081	28	2 layers
130	10.7	39	1.60373	28.3	2 layers
140	11.4	40.2	1.66426	28.8	2 layers
150	12.1	41.2	1.72268	29.1	2 layers
160	12.8	42	1.77917	29.2	2 layers
170	13.6	42.8	1.83393	29.2	2 layers
180	14.3	43.8	1.8871	29.5	2 layers
190	15.1	44.9	1.93881	29.8	2 layers
200	15.9	46	1.98918	30.1	Elutriation

Rice Shape 3 kg, Straight Blade					
ΔP across orifice (mmH_2O)	**ΔP across distributor (mmH_2O)**	**ΔP across distributor with particles (mmH_2O)**	**Reference velocity (m/s)**	**ΔP across bed (mmH_2O)**	**Observation**
0	0	0	0	0	Packed Bed
10	0.4	15.2	0.44479	14.8	Packed Bed
20	1.2	27.7	0.62903	26.5	Packed Bed
30	2.2	38.3	0.7704	36.1	Packed Bed
40	3	44.8	0.88959	41.8	Bubbling
50	3.9	44	0.99459	40.1	Bubbling
60	4.9	45.2	1.08952	40.3	Bubbling
70	5.6	46.1	1.17681	40.5	Bubbling
80	6.4	47.3	1.25807	40.9	Bubbling
90	7.6	48.5	1.33438	40.9	Bubbling
100	8.4	49.8	1.40656	41.4	Bubbling
110	9	50.8	1.47521	41.8	2 layers
120	9.9	51.8	1.54081	41.9	2 layers
130	10.7	53.3	1.60373	42.6	Elutriation

Flat Shape 1 kg, Straight Blade					
ΔP across orifice (mmH_2O)	**ΔP across distributor (mmH_2O)**	**ΔP across distributor with particles (mmH_2O)**	**Reference velocity (m/s)**	**ΔP across bed (mmH_2O)**	**Observation**
0	0	0	0	0	Packed Bed
10	0.4	9.4	0.44479	9	Packed Bed
20	1.2	14.8	0.62903	13.6	Bubbling
30	2.2	16	0.7704	13.8	Bubbling
40	3	16.5	0.88959	13.5	Slugging
50	3.9	17.7	0.99459	13.8	Slugging
60	4.9	19	1.08952	14.1	Slugging
70	5.6	20	1.17681	14.4	Slugging
80	6.4	21.2	1.25807	14.8	Slugging
90	7.6	22.3	1.33438	14.7	Slugging
100	8.4	23.5	1.40656	15.1	Slugging
110	9	24.7	1.47521	15.7	Slugging
120	9.9	26	1.54081	16.1	Slugging
130	10.7	27.2	1.60373	16.5	Swirling
140	11.4	28.2	1.66426	16.8	Swirling
150	12.1	29.2	1.72268	17.1	Swirling
160	12.8	30.5	1.77917	17.7	Swirling
170	13.6	31.5	1.83393	17.9	Swirling
180	14.3	32.5	1.8871	18.2	Swirling
190	15.1	33.5	1.93881	18.4	Swirling
200	15.9	34.4	1.98918	18.5	Swirling

Flat Shape 2 kg, Straight Blade					
ΔP across orifice (mmH_2O)	**ΔP across distributor (mmH_2O)**	**ΔP across distributor with particles (mmH_2O)**	**Reference velocity (m/s)**	**ΔP across bed (mmH_2O)**	**Observation**
0	0	0	0	0	Packed Bed
10	0.4	17.8	0.44479	17.4	Packed Bed
20	1.2	26.9	0.62903	25.7	Bubbling
30	2.2	28.8	0.7704	26.6	Bubbling
40	3	29.9	0.88959	26.9	Bubbling
50	3.9	31	0.99459	27.1	Bubbling
60	4.9	32.2	1.08952	27.3	Bubbling
70	5.6	33.2	1.17681	27.6	Bubbling
80	6.4	34.1	1.25807	27.7	Bubbling
90	7.6	35.3	1.33438	27.7	Bubbling
100	8.4	36.3	1.40656	27.9	Bubbling
110	9	37.2	1.47521	28.2	Bubbling
120	9.9	38.2	1.54081	28.3	2 layers
130	10.7	39.6	1.60373	28.9	2 layers
140	11.4	40.5	1.66426	29.1	2 layers
150	12.1	41.7	1.72268	29.6	2 layers
160	12.8	42.7	1.77917	29.9	2 layers
170	13.6	43.6	1.83393	30	2 layers
180	14.3	44.8	1.8871	30.5	Elutriation

Flat Shape 3kg, Straight Blade					
ΔP across orifice (mmH_2O)	**ΔP across distributor (mmH_2O)**	**ΔP across distributor with particles (mmH_2O)**	**Reference velocity (m/s)**	**ΔP across bed (mmH_2O)**	**Observation**
0	0	0	0	0	Packed Bed
10	0.4	25.8	0.44479	25.4	Packed Bed
20	1.2	39	0.62903	37.8	Bubbling
30	2.2	42	0.7704	39.8	Bubbling
40	3	43.3	0.88959	40.3	Bubbling
50	3.9	44.4	0.99459	40.5	Bubbling
60	4.9	45.5	1.08952	40.6	Bubbling
70	5.6	46.8	1.17681	41.2	Bubbling
80	6.4	47.8	1.25807	41.4	Bubbling
90	7.6	49.1	1.33438	41.5	Bubbling
100	8.4	50.1	1.40656	41.7	2 layers
110	9	51.1	1.47521	42.1	Elutriation

Spherical, 4mm 1 kg, Backward-Twist-Blade					
ΔP across orifice (mmH_2O)	**ΔP across distributor (mmH_2O)**	**ΔP across distributor with particles (mmH_2O)**	**Reference velocity (m/s)**	**ΔP across bed (mmH_2O)**	**Observation**
0	0	0	0	0	Packed Bed
10	0.1	5.2	0.44479	5.1	Packed Bed
20	0.1	9.4	0.62903	9.3	Packed Bed
30	0.3	12.9	0.7704	12.6	Packed Bed
40	0.5	14.1	0.88959	13.6	Bubbling
50	0.7	14.5	0.99459	13.8	Bubbling
60	1	13.7	1.08952	12.7	Slugging
70	1.3	14	1.17681	12.7	Slugging
80	1.8	14.3	1.25807	12.5	Slugging
90	2.2	14.7	1.33438	12.5	Slugging
100	2.6	15	1.40656	12.4	Slugging
110	2.9	15.5	1.47521	12.6	Slugging
120	3.4	16	1.54081	12.6	Slugging
130	3.7	16.4	1.60373	12.7	Slugging
140	4	16.7	1.66426	12.7	Slugging
150	4.2	16.7	1.72268	12.5	Slugging
160	5	17.7	1.77917	12.7	Slugging
170	5.4	18	1.83393	12.6	Slugging
180	5.8	18.3	1.8871	12.5	Slugging
190	6.1	18.1	1.93881	12	Swirling
200	6.4	18.4	1.98918	12	Swirling

Spherical, 4mm 2kg, Backward-Twist-Blade					
ΔP across orifice (mmH_2O)	**ΔP across distributor (mmH_2O)**	**ΔP across distributor with particles (mmH_2O)**	**Reference velocity (m/s)**	**ΔP across bed (mmH_2O)**	**Observation**
0	0	0	0	0	Packed Bed
10	0.1	10.6	0.44479	10.5	Packed Bed
20	0.1	18.6	0.62903	18.5	Packed Bed
30	0.3	25.2	0.7704	24.9	Bubbling
40	0.5	28.6	0.88959	28.1	Bubbling
50	0.7	27.8	0.99459	27.1	Bubbling
60	1	28.9	1.08952	27.9	Bubbling
70	1.3	29.2	1.17681	27.9	Bubbling
80	1.8	29.5	1.25807	27.7	Bubbling
90	2.2	30	1.33438	27.8	Bubbling
100	2.6	30.4	1.40656	27.8	Bubbling
110	2.9	30.8	1.47521	27.9	Bubbling
120	3.4	31.4	1.54081	28	Bubbling
130	3.7	31.8	1.60373	28.1	Bubbling
140	4	32.1	1.66426	28.1	Bubbling
150	4.2	32.6	1.72268	28.4	Bubbling
160	5	32.9	1.77917	27.9	2 layers
170	5.4	33.4	1.83393	28	2 layers
180	5.8	33.7	1.8871	27.9	2 layers
190	6.1	34.2	1.93881	28.1	2 layers
200	6.4	34.4	1.98918	28	Elutraition

Spherical, 4mm 3kg, Backward-Twist-Blade					
ΔP across orifice (mmH_2O)	**ΔP across distributor (mmH_2O)**	**ΔP across distributor with particles (mmH_2O)**	**Reference velocity (m/s)**	**ΔP across bed (mmH_2O)**	**Observation**
0	0	0	0	0	Packed Bed
10	0.1	15.1	0.44479	15	Packed Bed
20	0.1	26.7	0.62903	26.6	Packed Bed
30	0.3	35.6	0.7704	35.3	Packed Bed
40	0.5	40.6	0.88959	40.1	Bubbling
50	0.7	42.5	0.99459	41.8	Bubbling
60	1	42.6	1.08952	41.6	Bubbling
70	1.3	42.9	1.17681	41.6	Bubbling
80	1.8	43.6	1.25807	41.8	Bubbling
90	2.2	44.2	1.33438	42	Bubbling
100	2.6	44.7	1.40656	42.1	Bubbling
110	2.9	44.9	1.47521	42	Bubbling
120	3.4	45.6	1.54081	42.2	Bubbling
130	3.7	46	1.60373	42.3	Bubbling
140	4	46.6	1.66426	42.6	Bubbling
150	4.2	47.1	1.72268	42.9	Bubbling
160	5	47.3	1.77917	42.3	Bubbling
170	5.4	47.6	1.83393	42.2	Elutriation

Spherical, 5mm 1kg, Backward-Twist-Blade					
ΔP across orifice (mmH_2O)	**ΔP across distributor (mmH_2O)**	**ΔP across distributor with particles (mmH_2O)**	**Reference velocity (m/s)**	**ΔP across bed (mmH_2O)**	**Observation**
0	0	0	0	0	Packed Bed
10	0.1	3.1	0.44479	3	Packed Bed
20	0.1	5.8	0.62903	5.7	Packed Bed
30	0.3	8.3	0.7704	8	Packed Bed
40	0.5	10.6	0.88959	10.1	Packed Bed
50	0.7	12.9	0.99459	12.2	Packed Bed
60	1	14.5	1.08952	13.5	Bubbling
70	1.3	15.6	1.17681	14.3	Bubbling
80	1.8	16.1	1.25807	14.3	Bubbling
90	2.2	14.5	1.33438	12.3	Slugging
100	2.6	14.7	1.40656	12.1	Slugging
110	2.9	14.8	1.47521	11.9	Slugging
120	3.4	15	1.54081	11.6	Slugging
130	3.7	15.2	1.60373	11.5	Slugging
140	4	15.5	1.66426	11.5	Slugging
150	4.2	15.7	1.72268	11.5	Slugging
160	5	15.9	1.77917	10.9	Slugging
170	5.4	16.4	1.83393	11	Slugging
180	5.8	16.7	1.8871	10.9	Slugging
190	6.1	17.1	1.93881	11	Slugging
200	6.4	17.4	1.98918	11	Slugging

Spherical, 5mm 2kg, Backward-Twist-Blade					
ΔP across orifice (mmH_2O)	**ΔP across distributor (mmH_2O)**	**ΔP across distributor with particles (mmH_2O)**	**Reference velocity (m/s)**	**ΔP across bed (mmH_2O)**	**Observation**
0	0	0	0	0	Packed Bed
10	0.1	6.1	0.44479	6	Packed Bed
20	0.1	10.8	0.62903	10.7	Packed Bed
30	0.3	15	0.7704	14.7	Packed Bed
40	0.5	19.4	0.88959	18.9	Packed Bed
50	0.7	24.3	0.99459	23.6	Packed Bed
60	1	27.7	1.08952	26.7	Bubbling
70	1.3	28.7	1.17681	27.4	Bubbling
80	1.8	29.7	1.25807	27.9	Bubbling
90	2.2	29.9	1.33438	27.7	Bubbling
100	2.6	30.5	1.40656	27.9	Bubbling
110	2.9	31.3	1.47521	28.4	Bubbling
120	3.4	31.4	1.54081	28	Bubbling
130	3.7	31.7	1.60373	28	Bubbling
140	4	31.9	1.66426	27.9	Bubbling
150	4.2	32.3	1.72268	28.1	Bubbling
160	5	32.5	1.77917	27.5	Bubbling
170	5.4	32.8	1.83393	27.4	Bubbling
180	5.8	33	1.8871	27.2	Bubbling
190	6.1	33.3	1.93881	27.2	Bubbling
200	6.4	33.5	1.98918	27.1	Bubbling

Spherical, 5mm 3kg, Backward-Twist-Blade					
ΔP across orifice (mmH_2O)	**ΔP across distributor (mmH_2O)**	**ΔP across distributor with particles (mmH_2O)**	**Reference velocity (m/s)**	**ΔP across bed (mmH_2O)**	**Observation**
0	0	0	0	0	Packed Bed
10	0.1	8.3	0.44479	8.2	Packed Bed
20	0.1	14.9	0.62903	14.8	Packed Bed
30	0.3	21	0.7704	20.7	Packed Bed
40	0.5	26.7	0.88959	26.2	Packed Bed
50	0.7	33.2	0.99459	32.5	Packed Bed
60	1	38.4	1.08952	37.4	Packed Bed
70	1.3	39.4	1.17681	38.1	Bubbling
80	1.8	41	1.25807	39.2	Bubbling
90	2.2	42.2	1.33438	40	Bubbling
100	2.6	42.6	1.40656	40	Bubbling
110	2.9	43.4	1.47521	40.5	Bubbling
120	3.4	44	1.54081	40.6	Bubbling
130	3.7	44.6	1.60373	40.9	Bubbling
140	4	44.9	1.66426	40.9	Bubbling
150	4.2	45.3	1.72268	41.1	Bubbling
160	5	45.7	1.77917	40.7	Bubbling
170	5.4	46	1.83393	40.6	Bubbling
180	5.8	46.1	1.8871	40.3	Bubbling
190	6.1	46.9	1.93881	40.8	Bubbling
200	6.4	47.3	1.98918	40.9	Bubbling

Spherical, 6mm 1kg, Backward-Twist-Blade					
ΔP across orifice (mmH_2O)	**ΔP across distributor (mmH_2O)**	**ΔP across distributor with particles (mmH_2O)**	**Reference velocity (m/s)**	**ΔP across bed (mmH_2O)**	**Observation**
0	0	0	0	0	Packed Bed
10	0.1	2.5	0.44479	2.4	Packed Bed
20	0.1	4.7	0.62903	4.6	Packed Bed
30	0.3	6.7	0.7704	6.4	Packed Bed
40	0.5	8.7	0.88959	8.2	Packed Bed
50	0.7	10.6	0.99459	9.9	Packed Bed
60	1	12.8	1.08952	11.8	Packed Bed
70	1.3	14.7	1.17681	13.4	Packed Bed
80	1.8	15.6	1.25807	13.8	Bubbling
90	2.2	16.3	1.33438	14.1	Bubbling
100	2.6	16.5	1.40656	13.9	Bubbling
110	2.9	15.6	1.47521	12.7	Slugging
120	3.4	15.6	1.54081	12.2	Slugging
130	3.7	15.7	1.60373	12	Slugging
140	4	16	1.66426	12	Slugging
150	4.2	16.2	1.72268	12	Slugging
160	5	16.6	1.77917	11.6	Slugging
170	5.4	17.1	1.83393	11.7	Slugging
180	5.8	17.8	1.8871	12	Slugging
190	6.1	18.1	1.93881	12	Slugging
200	6.4	18.8	1.98918	12.4	Slugging

Spherical, 6mm 2kg, Backward-Twist-Blade					
ΔP across orifice (mmH_2O)	**ΔP across distributor (mmH_2O)**	**ΔP across distributor with particles (mmH_2O)**	**Reference velocity (m/s)**	**ΔP across bed (mmH_2O)**	**Observation**
0	0	0	0	0	Packed Bed
10	0.1	4.4	0.44479	4.3	Packed Bed
20	0.1	8	0.62903	7.9	Packed Bed
30	0.3	11.6	0.7704	11.3	Packed Bed
40	0.5	15.1	0.88959	14.6	Packed Bed
50	0.7	18.3	0.99459	17.6	Packed Bed
60	1	21.6	1.08952	20.6	Packed Bed
70	1.3	25.4	1.17681	24.1	Packed Bed
80	1.8	28.3	1.25807	26.5	Packed Bed
90	2.2	28.8	1.33438	26.6	Bubbling
100	2.6	29.8	1.40656	27.2	Bubbling
110	2.9	30.7	1.47521	27.8	Bubbling
120	3.4	31.4	1.54081	28	Bubbling
130	3.7	31.8	1.60373	28.1	Bubbling
140	4	32.1	1.66426	28.1	Bubbling
150	4.2	32.4	1.72268	28.2	Bubbling
160	5	32.8	1.77917	27.8	Bubbling
170	5.4	33.2	1.83393	27.8	Bubbling
180	5.8	33.6	1.8871	27.8	Bubbling
190	6.1	34	1.93881	27.9	Bubbling
200	6.4	34.2	1.98918	27.8	Bubbling

Spherical, 6mm 3kg, Backward-Twist-Blade					
ΔP across orifice (mmH_2O)	**ΔP across distributor (mmH_2O)**	**ΔP across distributor with particles (mmH_2O)**	**Reference velocity (m/s)**	**ΔP across bed (mmH_2O)**	**Observation**
0	0	0	0	0	Packed Bed
10	0.1	6.8	0.44479	6.7	Packed Bed
20	0.1	11.8	0.62903	11.7	Packed Bed
30	0.3	16.6	0.7704	16.3	Packed Bed
40	0.5	21.4	0.88959	20.9	Packed Bed
50	0.7	26.7	0.99459	26	Packed Bed
60	1	31.4	1.08952	30.4	Packed Bed
70	1.3	35.8	1.17681	34.5	Packed Bed
80	1.8	40.6	1.25807	38.8	Packed Bed
90	2.2	41.7	1.33438	39.5	Bubbling
100	2.6	42.8	1.40656	40.2	Bubbling
110	2.9	43.9	1.47521	41	Bubbling
120	3.4	44.6	1.54081	41.2	Bubbling
130	3.7	45.2	1.60373	41.5	Bubbling
140	4	45.8	1.66426	41.8	Bubbling
150	4.2	46.1	1.72268	41.9	Bubbling
160	5	46.5	1.77917	41.5	Bubbling
170	5.4	47	1.83393	41.6	Bubbling
180	5.8	47.5	1.8871	41.7	Bubbling
190	6.1	47.9	1.93881	41.8	Bubbling
200	6.4	48.3	1.98918	41.9	Bubbling

Rice Shape, 1kg, Backward-Twist-Blade					
ΔP across orifice (mmH_2O)	**ΔP across distributor (mmH_2O)**	**ΔP across distributor with particles (mmH_2O)**	**Reference velocity (m/s)**	**ΔP across bed (mmH_2O)**	**Observation**
0	0	0	0	0	Packed Bed
10	0.1	5.1	0.44479	5	Packed Bed
20	0.1	9.2	0.62903	9.1	Packed Bed
30	0.3	12.1	0.7704	11.8	Bubbling
40	0.5	13.5	0.88959	13	Bubbling
50	0.7	14.1	0.99459	13.4	Bubbling
60	1	14.4	1.08952	13.4	Bubbling
70	1.3	14.3	1.17681	13	Slugging
80	1.8	14.7	1.25807	12.9	Slugging
90	2.2	15.1	1.33438	12.9	Slugging
100	2.6	15.4	1.40656	12.8	Slugging
110	2.9	15.7	1.47521	12.8	Slugging
120	3.4	16.1	1.54081	12.7	Slugging
130	3.7	16.5	1.60373	12.8	Elutriation

Rice Shape, 2kg, Backward-Twist-Blade					
ΔP across orifice (mmH_2O)	**ΔP across distributor (mmH_2O)**	**ΔP across distributor with particles (mmH_2O)**	**Reference velocity (m/s)**	**ΔP across bed (mmH_2O)**	**Observation**
0	0	0	0	0	Packed Bed
10	0.1	9.1	0.44479	9	Packed Bed
20	0.1	15.8	0.62903	15.7	Packed Bed
30	0.3	21.9	0.7704	21.6	Packed Bed
40	0.5	26.2	0.88959	25.7	Packed Bed
50	0.7	27.2	0.99459	26.5	Bubbling
60	1	28.1	1.08952	27.1	Bubbling
70	1.3	28.5	1.17681	27.2	Bubbling
80	1.8	28.9	1.25807	27.1	Bubbling
90	2.2	29.3	1.33438	27.1	Bubbling
100	2.6	29.9	1.40656	27.3	Bubbling
110	2.9	30.4	1.47521	27.5	Bubbling
120	3.4	30.7	1.54081	27.3	Bubbling
130	3.7	31	1.60373	27.3	Elutriation

Rice Shape, 3kg, Backward-Twist-Blade					
ΔP across orifice (mmH_2O)	**ΔP across distributor (mmH_2O)**	**ΔP across distributor with particles (mmH_2O)**	**Reference velocity (m/s)**	**ΔP across bed (mmH_2O)**	**Observation**
0	0	0	0	0	Packed Bed
10	0.1	13.2	0.44479	13.1	Packed Bed
20	0.1	23.1	0.62903	23	Packed Bed
30	0.3	31.6	0.7704	31.3	Packed Bed
40	0.5	39.2	0.88959	38.7	Packed Bed
50	0.7	39.2	0.99459	38.5	Bubbling
60	1	40.2	1.08952	39.2	Bubbling
70	1.3	41	1.17681	39.7	Bubbling
80	1.8	41.4	1.25807	39.6	Bubbling
90	2.2	42	1.33438	39.8	Bubbling
100	2.6	42.8	1.40656	40.2	Elutriation

Flat Shape, 1kg, Backward-Twist-Blade					
ΔP across orifice (mmH_2O)	**ΔP across distributor (mmH_2O)**	**ΔP across distributor with particles (mmH_2O)**	**Reference velocity (m/s)**	**ΔP across bed (mmH_2O)**	**Observation**
0	0	0	0	0	Packed Bed
10	0.1	6.8	0.44479	6.7	Packed Bed
20	0.1	10.6	0.62903	10.5	Bubbling
30	0.3	11.8	0.7704	11.5	Bubbling
40	0.5	11.4	0.88959	10.9	Slugging
50	0.7	11.9	0.99459	11.2	Slugging
60	1	12.3	1.08952	11.3	Slugging
70	1.3	12.6	1.17681	11.3	Slugging
80	1.8	12.3	1.25807	10.5	Slugging
90	2.2	12.2	1.33438	10	Slugging
100	2.6	12.2	1.40656	9.6	Slugging
110	2.9	12.3	1.47521	9.4	Slugging
120	3.4	12.5	1.54081	9.1	Slugging
130	3.7	12.4	1.60373	8.7	Slugging
140	4	12.6	1.66426	8.6	Slugging
150	4.2	13	1.72268	8.8	Elutriation

Flat Shape, 2kg, Backward-Twist-Blade					
ΔP across orifice (mmH_2O)	**ΔP across distributor (mmH_2O)**	**ΔP across distributor with particles (mmH_2O)**	**Reference velocity (m/s)**	**ΔP across bed (mmH_2O)**	**Observation**
0	0	0	0	0	Packed Bed
10	0.1	14.6	0.44479	14.5	Packed Bed
20	0.1	21.9	0.62903	21.8	Bubbling
30	0.3	23.9	0.7704	23.6	Bubbling
40	0.5	25.5	0.88959	25	Bubbling
50	0.7	26.5	0.99459	25.8	Bubbling
60	1	26.8	1.08952	25.8	Bubbling
70	1.3	27.2	1.17681	25.9	Bubbling
80	1.8	27.4	1.25807	25.6	Elutriation

Flat Shape, 3kg, Backward-Twist-Blade					
ΔP across orifice (mmH_2O)	**ΔP across distributor (mmH_2O)**	**ΔP across distributor with particles (mmH_2O)**	**Reference velocity (m/s)**	**ΔP across bed (mmH_2O)**	**Observation**
0	0	0	0	0	Packed Bed
10	0.1	21.3	0.44479	21.2	Packed Bed
20	0.1	36	0.62903	35.9	Packed Bed
30	0.3	36.3	0.7704	36	Bubbling
40	0.5	38.3	0.88959	37.8	Bubbling
50	0.7	38.9	0.99459	38.2	Bubbling
60	1	39.1	1.08952	38.1	Bubbling
70	1.3	39.5	1.17681	38.2	Elutriation

APPENDIX C: PROJECT RECOGNITION

SCIENCE&ENGINEERING DESIGN EXHIBITION

UNIVERSITI TEKNOLOGI PETRONAS

Certificate of Participation

This Certificate is awarded to

Khor Jun Li
901024-08-5079

in recognition of his/her contribution as

Participant of
Final Year Project

"Gold"

in the 31st edition of

Science and Engineering Design Exhibition
Universiti Teknologi PETRONAS

held on
21st-22nd August 2013

Dr Lukman Bin AB Rahim,
Chairman,
Science and Engineering
Design Exhibition 31

Prof.Ir.Dr.Ahmad Fadzil
Mohamad Hani,
FASc, FIEM
Deputy Vice Chancellor
(Academic)

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