

**Experimental Studies on the  
Wavy Regime in Swirling Fluidized Bed**

By

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Dissertation is submitted in partial fulfillment of  
the requirement for the  
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**CERTIFICATION OF APPROVAL**

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TAN YINN SERN, 12874

A project dissertation submitted to the Petroleum Engineering Programme

Universiti Teknologi PETRONAS

in partial fulfilment of the requirements

for the Bachelor of Engineering (Hons) Degree in Mechanical Engineering

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September 2013

## **CERTIFICATION OF ORIGINALITY**

This is to certify 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.

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TAN YINN SERN

## **ACKNOWLEDGMENTS**

First of all, I would like to express my greatest gratitude to my campus, Universiti Teknologi PETRONAS (UTP) for providing a conducive learning environment in completing my Final Year Project. This project has allowed me to have a great exposure on the right methodology to carry out a research. Moreover, I have gained better understanding about prospect of Swirling Fluidized Bed (SFB), especially on wavy operating regime.

Many thanks go to my supervisor, Ms. Chin Yee Sing. Without her guidance and supervision throughout these two semesters, this project will not be succeeded. Her crucial contribution has kept my research work on the right track. Additionally, I want to thank Prof. Dr. Vijay R. Raghavan in giving me clear direction and useful advice, which eases my understanding towards SFB.

Lastly, I would like to say thank you to my parents and friends who morally supported and encouraged me during conducting this study.

## Abstract

Swirling Fluidized Bed is one of the noble designs using fluidization principle whereby particles in the bed will experience certain amount of fluid injection, either gas or liquid, generating sufficient reference velocity to create drag from down under the particles in order for fluidization to occur.

Swirling Fluidized Bed is unique as it has an array of distributor blades well arrange at the bed. When gas is injected through the bed setup at certain angles, swirling motion will be created besides fluidizing the particles. Fluidization occurred across the bed results in bed pressure drop and different flow regimes by varying the superficial velocity. Result is obtained through lab experiment by using a blade inclination angle of  $10^\circ$  and blade overlapping angle of  $18^\circ$  setup. Spherical particles with bed weight of 300g to 1000g are used in hydrodynamics study across all regimes with different particle size, particularly 4mm, 5mm and 6mm. This study clearly indicates the effects of bed weight and particle size, particularly in relatively shallow bed. Figure of Bed Pressure Drop vs Reference Velocity is plotted to show the trend and observation is recorded throughout the experiment. Moreover, slugging period and slugging periodicity were recorded to study their unique behavior with increasing of reference velocity.

Higher bed loading result in higher bed pressure drops due to higher bed resistance. Larger size particle show lower bed pressure drop, because interstitial spaces between them are larger, thus lesser resistance. In the slugging width and periodicity studies, crest formation and slug distance travelled are observed where at high reference velocity, crest formed at higher and distance travelled for the slug before disappearing is longer, thus resulting in bigger width and longer time taken. Additionally, starting and end time of wavy regime is recorded based on bed weights and particle size. Lower bed weights required lower reference velocity to achieve slugging and swirling due to lesser inertial forces. Smaller particle size results in lower reference velocity due to bed resistance because smaller particle has large surface area per volume, thus forming smaller interstitial space between particles. More air injected to the bed is capture and utilize them to perform slugging and swirling.

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### Abbreviations, Nomenclature, List of Symbols

<i>SFB</i>	<i>Swirling Fluidized Bed</i>
SFBC	Short-combustion-chamber Fluidised-Bed Combustor
<i>OPF</i>	<i>Oil Palm Frond</i>
$\Delta P_{mf}$	Pressure drop for minimum fluidization velocity
$U_{mf}$	Minimum fluidization velocity
$\Theta_i$	Blade inclination angle
$\Theta_o$	Blade overlapping angle
$\Theta^\circ$	Slugging width
$\Delta P$	Pressure difference
$\Delta P_{Distributor}$	Pressure drop across distributor
$\Delta P_{total}$	Total pressure drop
$\Delta P_{bed}$	Bed pressure drop
Q	Air flow rate
$A_o$	Orifice plate area
$C_d$	<i>Coefficient of discharge</i>
$\rho_{air}$	<i>Air density</i>
$\beta$	<i>Beta ratio</i>
D	<i>Pipe diameter</i>
d	<i>orifice diameter hole</i>

# CHAPTER 1

## Introduction

### 1.1 Background of Study

Fluidization is a process whereby fluid is allowed to propel through a bed of particles at a certain reference velocity whereby drag force acted is sufficient to overcome the weight of the particles. In this case, the particles start to exhibit fluid-like characteristic and is said to be fluidized. Before swirling fluidized bed (SFB) is invented, conventional fluidized bed is used in fluidization technology. According to Goo [1], conventional fluidized bed has a few disadvantages compared to swirling fluidized bed because it has restriction in gas flow rate and limitation on size, shape and magnitude of distribution. In order to overcome this sort of problem, few advanced techniques were invented such as centrifugal fluidized bed, vigor-fluidized bed and tapered fluidized bed. In the recent years, swirling fluidized bed is invented featuring an array of annular blade distributor in the experiment setup. Fluid propelled through the blades will show swirling motion flow until it exits the cylindrical wall according to blade inclination angle and blade overlapping angle used. By using these blades, gas will flow in axial and radial direction to form swirling motion when it passes through the distributor.



*Figure 1.1: An actual distributor of a Swirling Fluidized Bed*

## 1.2 Problem Statement

Swirling Fluidized Bed (SFB) is quite new in the field of fluidization engineering. This new design and concept has led to inadequate research and experiment to prove and show its own characteristics and behaviours. Problems such as efficiency, design and usage have yet to be fully discovered though there were some literatures showing that this technique has been brought to use in some specific industries such as drying of particles and heat exchangers.

In SFB, bed configuration plays an important role in determining the bed pressure drop and superficial velocity as these two major factors will reflect on the system performance. Configuration can be classified into two parts which is the blades arrangement and particles used. Minute changes between these two parts may bring significant effect to the output. Arising from literature studies, no research of SFB on slugging regime, specifically slugging period and slugging width have been done so far and hopefully this project can fill up the relatively barren SFB researches.

## 1.3 Objectives

The objective of this project is to develop an understanding on how bed characteristic affect the hydrodynamics of SFB. In order to discover the hydrodynamics, a few bed parameters need to be taken into consideration, such as:

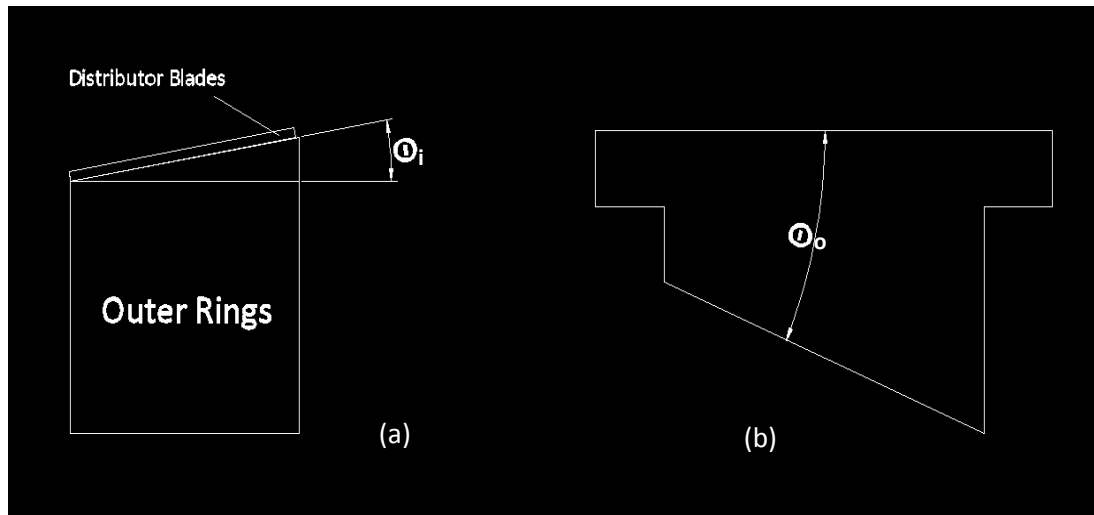
- i. Particle shape
- ii. Particle size
- iii. Bed weight

Distributor Blades Inclination Angle,  $\Theta_i$  and Overlapping Angle,  $\Theta_o$

Hydrodynamics of Swirling Fluidized Bed:

- i. Flow regimes across fluidization
- ii. Difference in pressure drop across the bed

In this project, apart from experimenting all flow regimes in SFB, the author will also focus on discovering slugging regime properties, by studying how the effect of bed resistance reflect on slugging width and slugging periodicity.



*Figure 1.2: Blade inclination angle and blade overlapping angle*

#### **1.4 Scope of Study**

Basically, SFB can be categorized into two types, which are relatively shallow bed and relatively deep bed. These two types of bed behave differently and they have their own characteristics, for instance, relatively shallow bed has slugging or wavy regime but relatively deep bed has two layer regimes instead. The scope of this project is set to determine the hydrodynamics characteristics for relatively shallow beds by visual inspection and bed pressure drop measurement. Additionally, study on specific slugging characteristics like slugging periodicity and slugging width will be taken into consideration as well. The author will also identify what is the range of bed weight for relatively shallow bed as well as the starting point and end point for slugging regimes to occur.

## CHAPTER 2

### Literature Review

#### 2.1 Basic Principle of Fluidization

Sreenivasan and Raghavan [2], explains that fluidization is a process where solid particles exhibit fluid-like characteristic through suspension in gas or liquid. During the process, pressure drop occurred between the bed and air intake. According to Sreenivasan and Raghavan [2], Faizal *et al.*[3] and Batcha and Raghavan [4], they observed that increasing rate of fluid flow, or in other words, reference velocity, through the bed will lead to pressure drop after minimum fluidization. At this moment, the drag force from the fluid which exerted to the bed particles will counterbalances the particles weight and start to behave like a fluid. Thus the bed is said to be fluidized. The advantages of increasing the mobility of a solid through fluidization contribute some major effects to the industry and it has bright future in solid-gas processing activity.

Fueyo and Dopazo [5] state that fluidization is a process where bed of solid particles can obtain fluid-like properties by passing fluid through it. When fluid flow rate is low, the fluid will flow through the particle interstitial space whereas the bed still remains as packed bed. When the fluid flow increases, drag force exerted at the bed will increase gradually and this led to bed expansion and particles will start to get suspended. At this stage, it is said to be in incipient fluidization. When higher fluid flow rates are forced through the bed, bubble is formed among the particles and move up to escape to the surroundings. Further increase in velocity will result in slugging which is formation of slugs whereby bubbles will join together to become a cavity to occupy a whole cross section of the bed. Lastly, transport is the final stage of fluidization where particles will be blown out from the bed provided that sufficient velocity is supplied.

Fluidization concept is used to dry bed grain, and it is now commercialized as it has high potential in drying high moist grains like paddy and soybean. Fluidized bed managed to increase the drying rate as compared to conventional while reducing energy consumption as well, as explained by

Soponronnarit [6]. Moreover, it was also figured out that this technique brings uniform drying as grains are all well mixed together, at the same time increasing drying capacity due to better heat transfer, thus reducing cost and energy usage significantly. This outcome is further proven by Faizal *et al.* [7] where they shared the same fluidization concept. The author thinks that this technique has better reliability, so further modification or research on swirling fluidized bed can result in other better findings.

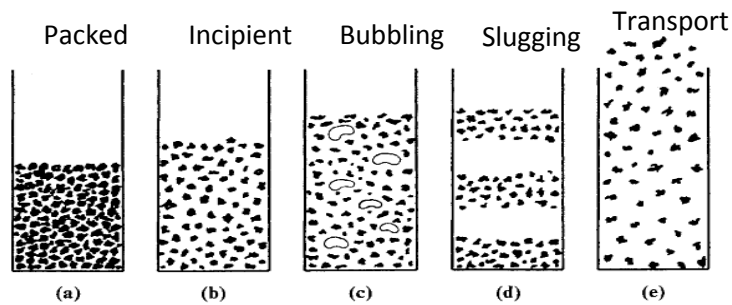


Figure 2.1: Fluidization states

Figure extracted from Fueyo and Dopazo[4]

## 2.2 Swirling Fluidized Bed (SFB)

To have a better understanding on SFB, basically it has few operation regimes. Figure 1.4 shows operation regimes and the trend of how bed pressure drop behaves against reference velocity.

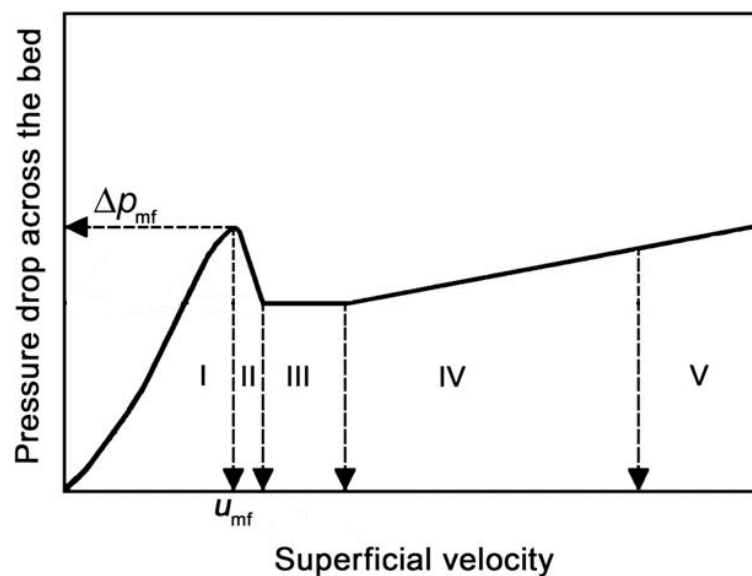


Figure 2.2: Pressure drop profile in SFB, Reproduced from [4]

Region I: Packed bed regime

Region II: Incipient regime

Region III: Wavy Regime/Two Layer regime

Region IV: Swirling regime

Region V: Entrainment regime

$\Delta P_{mf}$ : Pressure drop for minimum fluidization velocity

$U_{mf}$ : Minimum fluidization velocity

From Figure 1.4, it can be understood and giving a rough idea on the behaviour and characteristic of SFB.

Characteristic of swirling fluidized bed that is highlighted by Faizal *et al.* [3] that in a typical fluidized bed, gas is injected to the bed through perforated-plate distributor where the gas possess three components which are axial, radial and tangential. In conventional bed, axial momentum exerted to the bed is relatively too great compared to radial and tangential components. This lead to vertical mixing rather than lateral mixing and elutriation problem happens. Instead, Shu *et al.* [8] explicated that inclined gas injection in SFB causes swirling motion of particles on confined circular path with much lower tangential force when fluidizing the bed. In this case, elutriation can be reduced significantly. Invention of using annular distributor to produce rather equal momentum distribution in SFB has the following advantages compared to the conventional bed:

- a) Elutriation is reduced significantly
- b) Relatively lower bed pressure drop thus higher efficiency
- c) Stable mixing of particles
- d) Reduction in bubbles and slugging

Apart from having dominant lateral mixing, SFB has better solid-fluid contacts as well. This statement is proven by Faizal *et al.* [9] as swirling fluidized bed can enhance heat transfer rates, thus producing better outcome than conventional bed. In conventional fluidized bed, convective augmentation of heat transfer coefficient is not constant but decreases continuously from bottom layer until upper surface.



Kaewklum and Kuprianov [10] also state that swirling fluidized bed technique is used to improve the efficiency of combustor and has proven by addressing two advantages which are:

- a. SFB prevent growth of large bubbles
- b. Particle size flexibility

Moreover, Kuprianov *et al.* [11] has done a research by comparing conventional fluidized bed combustion to swirling fluidized bed combustion technique for burning of rice husk. Initially, conventional type combustor only manages to perform an efficiency from range 81-98% as the lower range is caused by CO emission and unburned carbon. After applying swirling fluidized bed technique, efficiency increased drastically to 98-99%.

Another author Faizal *et al.* [7] states that SFB technique is used on drying oil palm frond (OPF). Moisture rate removal in OPF can be increased greatly, furthermore, process such as cooling and mixing can be implemented using the same SFB as well and this can save up a lot of cost. Distributor design has been improved by extending the centre body straight down along the plenum chamber to avoid fluid expansion. This makes the fluid swirl before entering the distributor. Energy loss is minimized and efficiency is increased by then.

Apart from drying oil palm frond, this method is further developed to dry rice-husk, an advance way of doing with the same idea as compared to Soponronnarit [6]. Madhiyanon *et al.* [12] proposed that short-combustion-chamber fluidised-bed combustor (SFBC) can be implemented as an upgrade to Soponronnarit's idea. By using this method, combustion efficiency is further increased up to 98% and maximum heat rate intensity up to  $0.80 \text{ MWm}^{-2}$ . Apart from increasing its efficiency, this method also eliminates the need of using secondary solid bed materials such as sand, which has a function of retaining the heat within rice-husk. SFBC manages to produce, in fact, better output compared to conventional ones.

### 2.3 Hydrodynamic characteristic

Sreenivasan and Raghavan [2] state that a feature that distinguishes SFB from a conventional fluidized bed is that the pressure drop in swirling mode increased with reference velocity after minimum fluidization with the explanation of it is proportional to the bed centrifugal weight. Moreover, Sreenivasan and Raghavan [2], Faizal *et al.* [3] and Batcha and Raghavan [4] also found that the size and type of annular blade do not contribute much on the effect on fluidization as compared to blade openings, which is blade overlapping angle and particle size.

In an experimental study conducted by Paulose [13], it is observed that increasing blade overlapping angle can considerably decrease the bed pressure drop. However, further increase of angle which is more than 17% will not reduce bed pressure drop any further.

According to Paul [14], variation of distributor pressure drop with reference velocity reveals that the distributor pressure drop decreases with angle of fluid injection. Study of bed behaviour shows that reference velocity required for initiating various bed behaviour increases with particle size as well as particle density. Bed behaviour such as linear variation of bed pressure drop, constant bed pressure drop and sudden increase or decrease in bed pressure drop are directly influenced by reference velocity.

Bed pressure drop is the pressure difference between total pressure drop and distributor pressure drop. Sobrino *et al.* [15] highlighted the importance of distributor pressure drop which disperses the gas as uniformly as possible over the whole cross-section of the bed. If the pressure drop is very low, the air will enter the bed in the zone of lowest pressure drop and it will cause a non-uniform distribution of air flow inside the bed. Meanwhile, in fluidized bed processes, bed pressure drop is the main element to define the power required for fluidization and justifies the behaviour of the flow regime. Figure 1.5 is shown below to show the position of all pressure drops in a fluidized bed where P1 to P3 is total pressure drop,  $\Delta P_{Total}$  and P2 to P3 is distributor pressure drop,  $\Delta P_{Distributor}$ . To get bed pressure drop, the formula below is used.

$$\Delta P_{Bed} = \Delta P_{Total} - \Delta P_{Distributor}$$

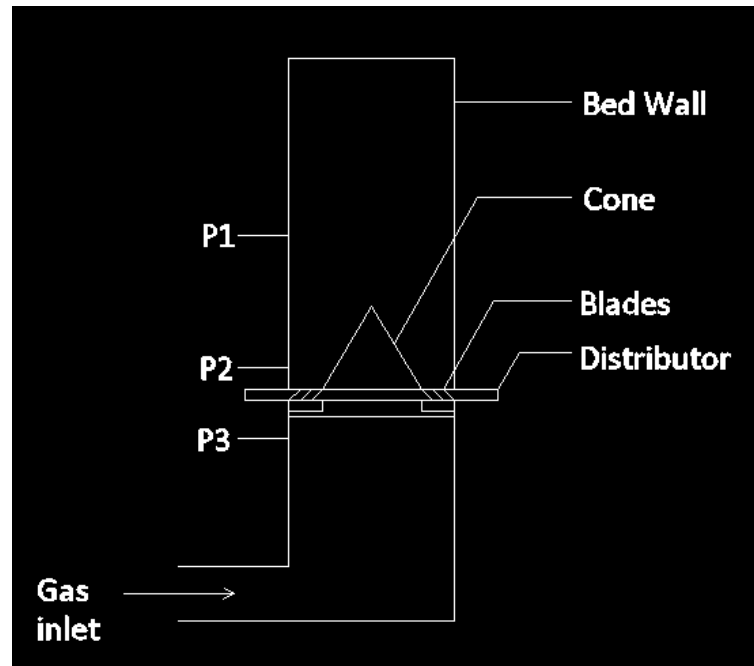


Figure 2.3: Schematic diagram for bed setup

Kumar and Murthy [16] claimed that the minimum reference velocity for the bed to swirl is dependent on static bed depth, fluid inlet diameter, column diameter, number of fluid inlets and particle properties. When the static bed height exceed certain satisfactory limit, the solids in the lower portion of the bed nearer to fluid inlets are found to be in swirling motion completely, but the top portion of the bed is performing bubbling motion instead of swirling. In this case, stable swirling of entire bed has not been possible at any gas flow rate.

Not much research has been done so far in shallow bed particularly on the wavy regime and this is definitely an advantage to perform experimental studies on how bed characteristics influence particles fluidization hydrodynamics.

## **CHAPTER 3**

### **Methodology**

#### **3.0 Project Activities**

Experimental study on wavy regime in swirling fluidized bed is a tedious project and needs a well-planned project activities flow chart and Gantt chart to act as a guideline for the author to complete his work successfully. The plan will be separated into two parts which FYP 1 and FYP 2. In FYP 1, the author will focus on preliminary research and literature studies so that more information on SFB can be obtained and understand well before the experiment starts. Before conducting the experiment, scope and methodology of the project need to be specified in order to have a clear direction on what the author is going to achieve throughout the whole project. Moreover, the author takes the initiative to familiarize himself with the lab setup. By doing so, the author attempted a few trial runs to understand the flow regimes in SFB using visual inspection and bed pressure drop is taken as to compare the trend with other researches available in the literature review.

In FYP 2, the author will start his experimental work, using spherical shape particles with the size of 3mm to 6mm. Bed weight of 300g will be set as the starting point and the experiment will be conducted with an increment of 100g of particles until the end of slugging regime. Blade setup of 10° inclination angle and 18° overlapping angle will be used for the distributor blade arrangement. Apart from using the above parameters, the author will also try on other particles shapes and different blade setup for further hydrodynamics study. After getting all the data from experiment, the author will analyse the data and interpret them before reporting and documentation.



*Figure 3.1: Project activity flow*

### 3.1 Gantt Chart and Key Milestones

#### Gantt Chart and Milestone for FYP 1

No.	Details/Week	January			February				March			April					
		1	2	3	4	5	6	7	8	9	10	11	12	13	14		
1	Topic Selection								Mid Sem Break								
2	Proposal Submission																
3	Proposal approval by research cluster																
4	Preliminary research/literature review																
5	Extended Proposal Defence																
6	Learn how to use experiment setup																
7	Proposal Defence Presentation																
8	Experimental work -Test Run on Lab Setup -Error Verification -Pressure Gauge Calibration																
9	Interim Report Preparation (Draft)																
10	Interim Report Submission																

#### Key Milestones

1. Extended Proposal Defence
2. Proposal Defence Presentation
3. Interim Report Submission

## Gantt Chart and Milestone for FYP 2

No.	Details/Week	May			June				July				August				
		1	2	3	4	5	6	7	8	9	10	11	12	13	14		
1	Experimental work -Manipulate bed weight -Manipulate particle size -Use camera to capture slugging width -Use of stopwatch to time slugging periodicity	Red	Red	Red	Red	Red	Red	Red	Mid Sem Break								
2	Writing of Progress Report					Yellow	Yellow	Yellow		Yellow							
3	Data Analysis			Green	Green	Green	Green	Green		Green							
4	Writing of draft final report										Blue	Blue	Blue				
5	Completion of dissertation (soft bound)													Orange	Orange		
6	Writing of technical paper																
7	Preparation for Oral Presentation															Dark Blue	Dark Blue
8	Completion of dissertation (hard bound)																Dark Green

### Key Milestones

1. Progress Report



2. Draft Final Report



3. Completion of soft bound dissertation



4. Technical Paper



5. Oral Presentation



6. Completion of hard bound dissertation



### 3.2 Tools and Apparatus

Swirling fluidized bed apparatus can be classified into three major segments which are Input, Test Bench and Output. Figure 3.2 below shows the breakdown of each segment.

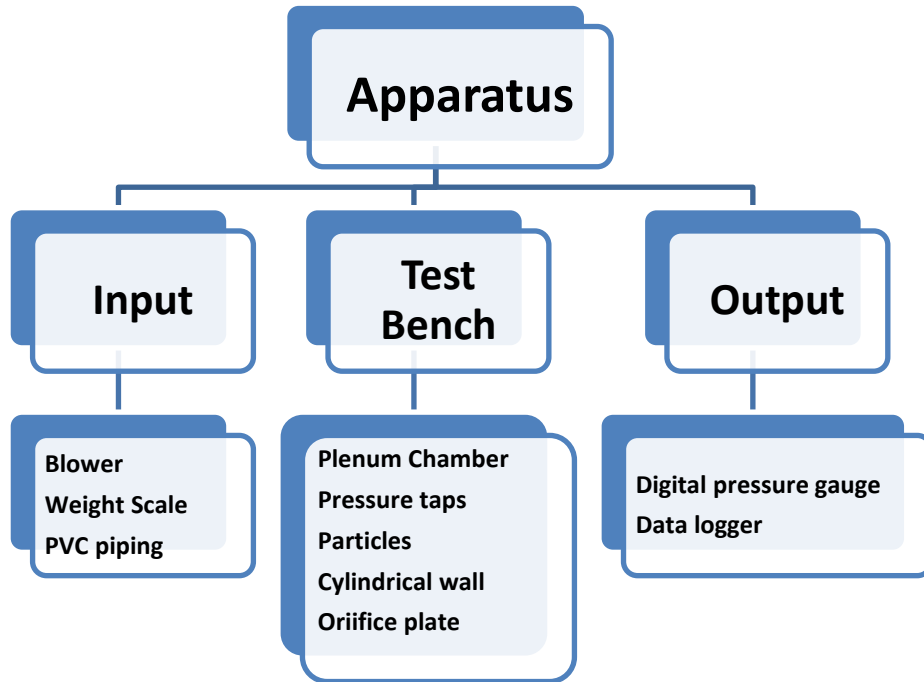


Figure 3.2: Apparatus used in experiment

Data logger is used at the output of the lab setup. Figure 8 shows the model of data logger.



Figure 3.3: GRAPHTEC midi logger GL820





*Figure 3.4: Actual experiment setup in lab*

From Figure 3.4, it has an array of trapezoidal shape annular blades fitted on the lab setup to form a spiral like distributor. Cylindrical bed wall and the distributor are placed on a plenum chamber, the path where gas injection takes place. Plenum chamber is then connected to the blower through pipes together with orifices to measure the air flow rate. A hollow metal cone is fixed at the centre of the bed to eliminate “dead zone”. Pressure tapings are used to alter pressure measurement for orifice pressure drop and distributor pressure drop. Wind blower is installed to provide gas injection to the bed which can go up to 3.5m/s. All these setup are significant in hydrodynamics study but there are still other equipment is needed to capture slugging width and slugging periodicity for extensive study on slugging regimes. In order to capture slugging width, Nikon D90 Camera is used to take the image of slugging regime at particular bed weight and superficial velocity. These pictures will be analysed to determine the slugging width. Next, Heliocentris CG-501 stopwatch is used to obtain slugging periodicity in each of the slugging occurred throughout the author’s experiment. All these data will be taken and tabulated for future data analysis.



Figure 3.5: Heliocentris CG-501 Stopwatch

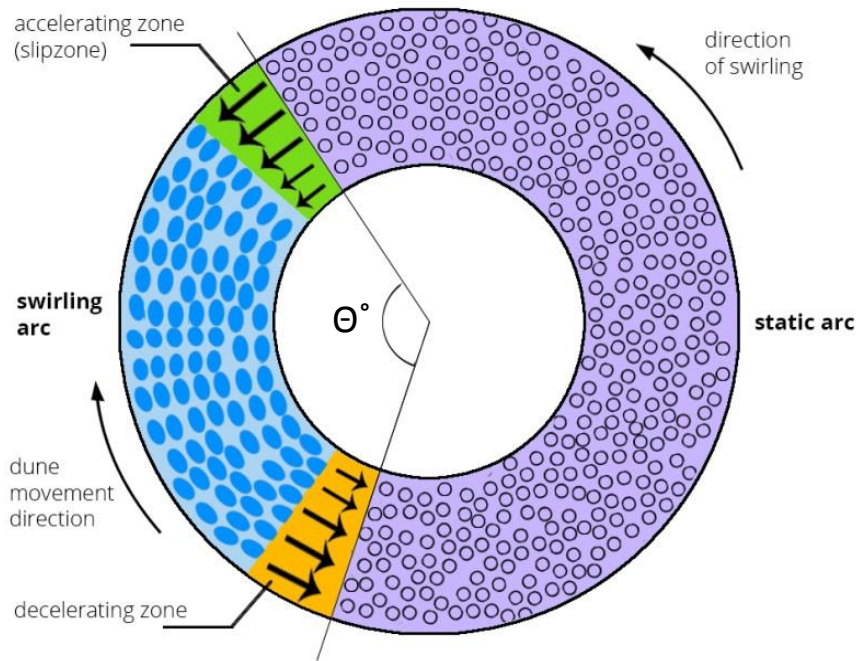


Figure 3.6: Schematic diagram for slugging width

### 3.3 Experiment Procedures

- i. 60 Blades of 18° overlapping angle are arranged on 10° inner ring at Bakelite and 10° outer ring is placed on the blades to form spiral shape distributor.
- ii. A thin carbon steel disk is placed on top of the inner rings and screw to the centre of the bed to hold the blades in place.
- iii. A metal cone is screwed to the centre of the bed as well as to eliminate “dead zone”.
- iv. Perspex cylindrical wall is place on top of the outer rings and screwed to the plenum chamber with bolts and nuts to hold the distributor tightly.
- v. Test run on the setup is conducted by switching on the blower at certain amount of reference velocity as to inspect on any air leakage on the setup.
- vi. Blower is switched on once again to measure distributor pressure drop at air flow rates, which is measured in the unit of mmH<sub>2</sub>O.
- vii. 300g of 3mm spherical particles is measured using weighing scale and pour into the bed.
- viii. The experiment is conducted by measuring distributor pressure drop with particles at specific air flow rates.
- ix. When slugging regime occurred, slugging width is capture using camera and slugging periodicity is measured using stop watch throughout the regime.
- x. All data will be tabulated into a table for future analysis.
- xi. Experiment is continued with an increment of 100g particles until slugging regime is no longer inspected at the particular bed weight.
- xii. Experiment is repeated using 4mm, 5mm and 6mm particles with the same blades setup.

## CHAPTER 4

### Result and Discussions

In this study, the term “Reference Velocity” had been used in place of “Superficial Velocity” that appeared in all literature referred to since they were analogous to each other.

#### 4.1 Basic Calculation

##### 4.1.1 Bed Pressure Drop, $\Delta P$

Bed pressure drop is calculated by subtracting distributor pressure drop with particles from the bed pressure drop of an empty distributor. Both distributor pressure drops can be obtained by altering the pressure tapings to get desired result.

$$\Delta P_{Bed} = \Delta P_{Distributor\ with\ particles} - \Delta P_{Distributor}$$

##### 4.1.2 Reference Velocity, $V_{ref}$

Reference velocity is obtained by measuring the air flow rates through the orifice plate. Value shown in pressure gauge is in the unit of mmH<sub>2</sub>O. In order to change the unit to m/s, Goo [1] has come out with the formula as shown below:

$$V_{reference} = 0.2249\sqrt{\text{Pressure Difference at Orifice, } \Delta P}$$

#### 4.2 Observations

In SFB, the author found out that it can be classified into two beds, which is relative shallow bed and relative deep bed. This experiment only covers hydrodynamics study at relative shallow bed as wavy regime only occurs at shallow beds, whereas bubbling bed occurs at relative deep bed instead.

In relative shallow bed, it basically behaves five particular regimes, which are packed, incipient, wavy, swirling and elutriation, as mentioned by Sreenivasan and Raghavan [2] and Batcha and Raghavan [4].

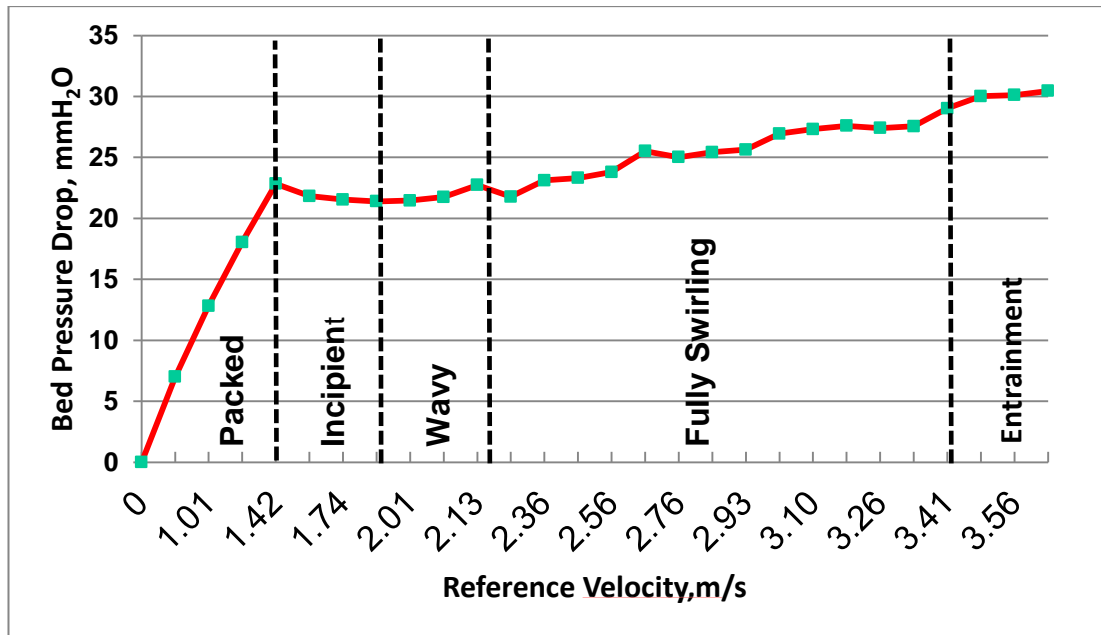


Figure 4.1: Operating Regimes in Swirling Fluidized Bed

In packed bed regime, particles do not move as more air is required to be injected before reaching minimum fluidization. Steep curve trend is observed showing massive pressure drop as air is blocked by the particles. Incipient regime comes after packed bed where particles start to vibrate and agitate, reaching the verge of minor slugging. When more air is injected, particles start to behave wavy pattern as it will move at certain arc length whereby other part of the bed will remain as static dune. Moving dune will be accumulated at the back of static dune and the front of static dune will start to move, forming a continuous process. Next, when higher air velocity is propelled to the particles, swirling motion is noticeable. Particles will swirl around the bed, mixing of particles happens vigorously among themselves. This regime is the most preferred one because it increases the rate of mixing of particles and heat transfer rates as well. At extreme gas velocity, elutriation or entrainment regime occurs. Particles tend to be blown out from the cylindrical wall progressively, resulting in too vigorous mixing. Bed pressure drop curve showed that after reaching minimum fluidization velocity, pressure drop will decrease by a little and then increase gradually to the end of elutriation process, this is because more air is required to overcome bed resistance.

In this experiment, the author has discovered a new observation which is “extremely shallow beds” where particles added to the bed have not sufficiently

covered the whole bed area. In this case, when gas is injected, packed bed and incipient fluidization still behaves the same but when it reaches minimum fluidization velocity, particles are being pushed and stack together to one area while small amount of particles swirl at fast velocity. This phenomenon goes on and on to cover other bed area simultaneously. In this case, particles do not perform the usual wavy behaviour and this scenario is not preferred because most of the gas injected to the bed is wasted, thus more gas and energy is needed to fluidize the bed, lead to drop of efficiency. Table 4.1 summarizes bed weight for extremely shallow beds and relative shallow beds.

*Table 4.1: Bed Classification*

Parameters	Diameter	Extremely Shallow Bed	Relatively Shallow Bed	Relatively Deep Bed
Particles 1	4mm	300g – 400g	500g – 700g	800g
Particles 2	5mm	300g – 500g	600g – 900g	1000g
Particles 3	6mm	300g – 600g	700g – 1000g	1100g

Referring to an extremely shallow bed, vacant spaces were observed. This phenomenon is not recommended because gas injected to the bed is not fully utilized and this shows low efficiency. Wastage of reacting gas is not preferred and these bed weights are said to be extremely shallow bed.



*Figure 4.2: Vacant Space Shown in Extremely Shallow Bed*

Referring to relatively shallow bed, no more vacant space is shown during slugging and this is said to be the starting point of slugging regime in swirling fluidized bed. Reacting gas injected can be use efficiently to swirl the bed and this is a more preferable ones.



*Figure 4.3: Absence of Vacant Space in Shallow Bed*

### **4.3 Effect of Particle Size**

Figure 4.4 indicates that increase of particle size result in lesser pressure drop. The reason behind this trend is because interstitial spaces between particles are not the same. 4mm particles has larger surface area and smaller space between particles, therefore, these spaces manage to create more blockage to trap more air before air leaves the bed and this also lead to higher bed pressure drop. Adversely, 6mm particles have wider interstitial space between particles which leads to the ease of air escaping from the bed. Referring to Figure 4.4, 6mm particles yield lower pressure drop and this further proves that bed with bigger particle size has lesser bed resistance. Moreover, effect of particle size can be related to surface friction of particles. At the same bed weight, smaller particle size has better surface friction due to the principal of surface area. When surface area is larger, more energy is needed to overcome the friction before fluidization happens and this result in higher bed

pressure drop. On the other hand, large particles have lesser surface friction and air can flow through them comparatively easier and this indicates that bed pressure drop is relatively lower than smaller particles. So, the bed will expand slower and it takes more reference velocity before reaching elutriation. To summarize the above statement, larger particles have better advantage because it can withstand higher reference velocity and swirl longer throughout and this is feasible in practical wise. Conversely, smaller particles has better bed resistance, which can create more blockage to trap the air, thus utilizing most of the air kinetic energy to achieve higher fluidization efficiency. Ultimately, feasibility between energy used and fluidization needs to be achieved to produce the best output.

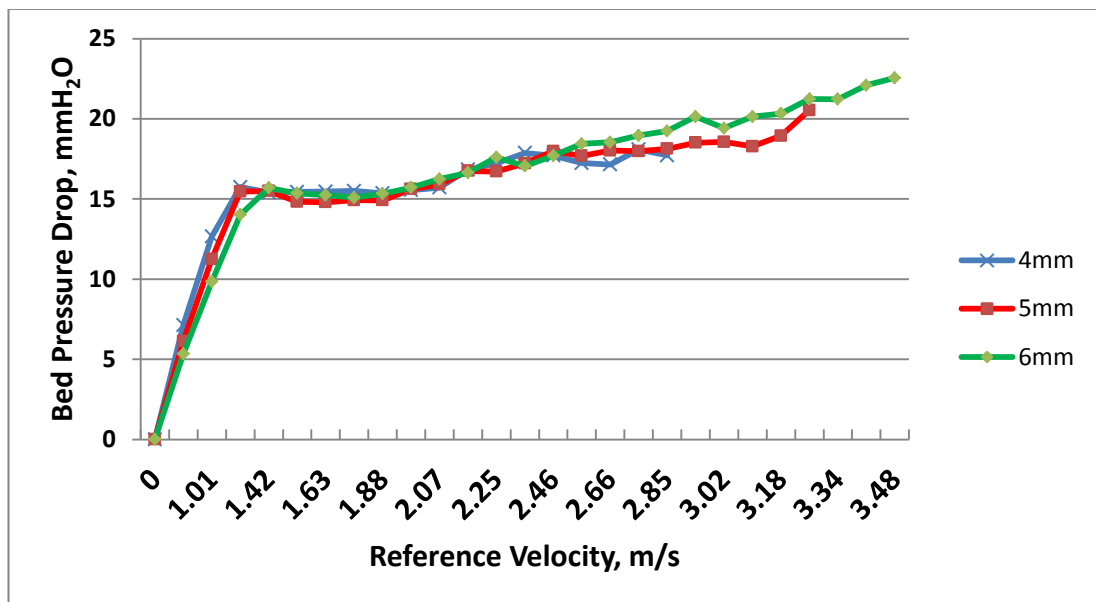


Figure 4.4: Bed Pressure Drop against Reference Velocity of 700g Spherical Particles at Different Size

#### 4.4 Effect of Bed Loading

Bed weights ranging from 300g to 1000g with an additional of 100g per increment for different particles size were experimented to study the relationship between the effects of bed weights against bed pressure drop. Referring to Figure 4.5, the trends show that higher bed weights results in higher bed pressure drop and this relationship is directly proportional to the air flow. Regardless of particle size, increase of bed weights increase bed surface area between particles as well as bed resistance. When this happens, air injected encounters more blockages and the air has



lesser air passages for it to flow through, thus more air tends to be trapped within the particles. In this case, only little air is allowed to pass through the bed; therefore, higher reference velocity is needed to fluidize the bed. It can be further explained if flour is used instead of particles for example. Whole bed area is fully covered and no spaces for the air to flow through the bed. Extreme bed pressure drop occurs so more reference velocity is required for fluidization to occur. The major difference between inlet and outlet air pressure across the bed reflects directly to bed pressure drop and this can be proven by the author's data collection. Practically, energy saving and efficiency is the main concern, so, higher bed loading is usually not the preference of all. Fluidization quality should be focused instead to achieve to best outcome.

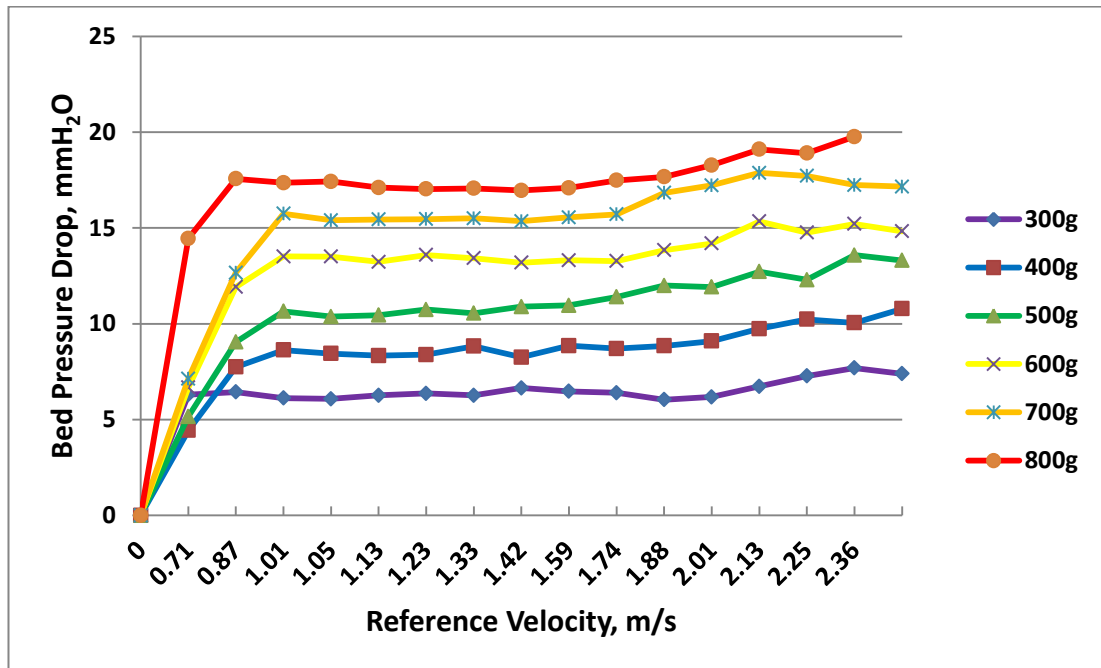


Figure 4.5: Bed Pressure Drop against Reference Velocity of 4mm Spherical Particles

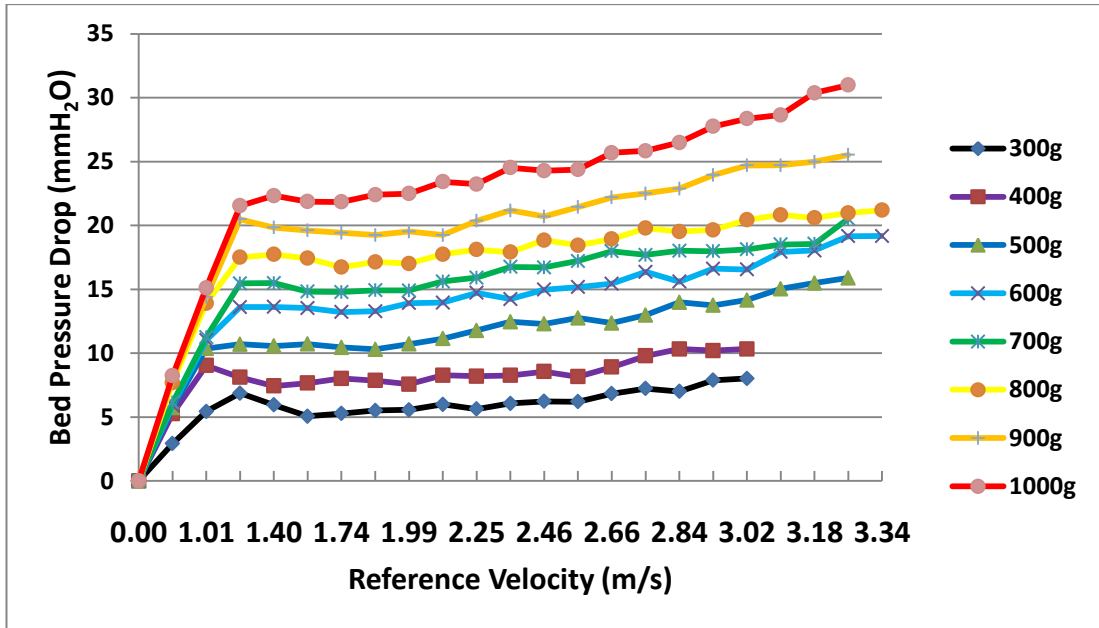


Figure 4.6: Bed Pressure Drop against Reference Velocity of 5mm Spherical Particles

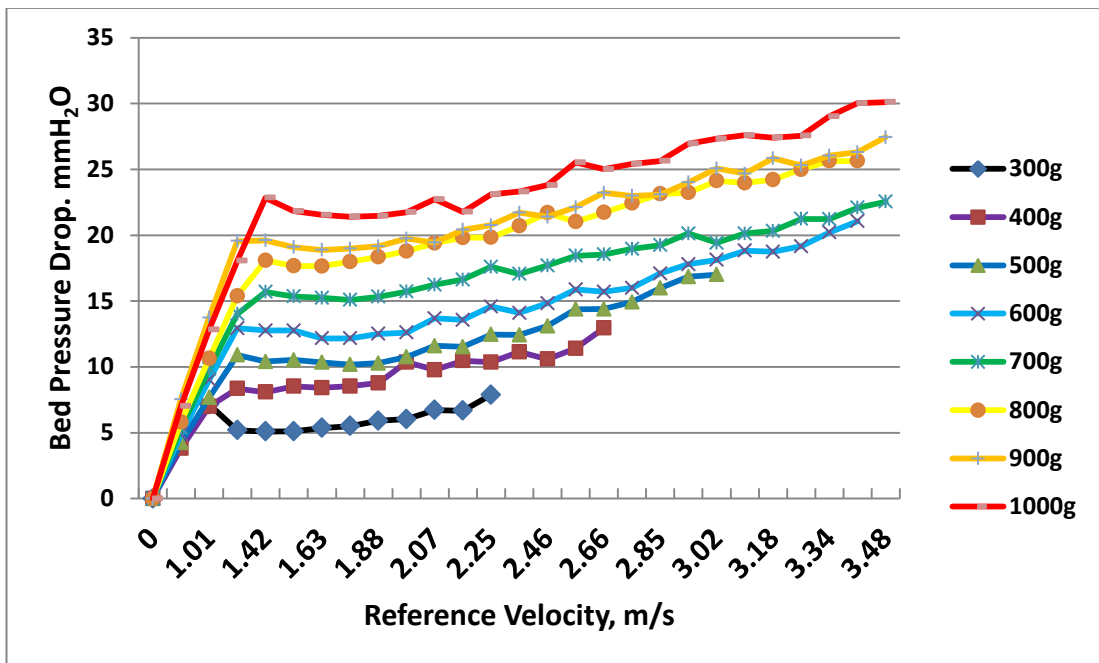


Figure 4.7: Bed Pressure Drop against Reference Velocity of 6mm Spherical Particles

From the discussion above, hydrodynamics of wavy regime in SFB has been done. Apart from that, new observation has been discovered, which the author has categorized them into extremely shallow beds and relatively shallow beds. Differences between them can be easily identified, by just observing slugging regime. This new observation has shown empty spaces during slugging on extremely shallow beds, which indicates a major waste of energy injection to the bed, thus not preferred. Referring to second part of the author's objective, the author needs to come out with an analysis regarding slugging width and slugging period.

#### **4.5 Slugging Width & Slugging Periodicity**

In swirling fluidized bed, there are five basic operating regimes in relatively shallow bed which are packed, incipient, wavy, swirling and then entrainment. Specific studies in wavy regime have been done to figure out what is the width and period of slugging at different types of particles and bed weight. First of all, slugging occurs after achieving minimum fluidization, where the bed starts to slug a little and then swirling takes place, consequently swirling motion will increase gradually proportional to air reference velocity until entrainment regime is observed. During slugging, two dunes will form separately at each side of the bed which are static and moving dune. The head of moving dune will go forward, meeting the tail of static dune and by then, the static dune will become a moving dune to go forward, forming a continuous process of swirling motion, depending on the incoming reference velocity. Crest of particles form the head of moving dune and once the crest meet static dune, the crest will disappear and it forms again at another of moving dune.

To determine what are the slugging width and periodicity, a detail observation is done by measuring what is the length of slugging width, which is the distance travelled between the starting point and end point of crest formation, as well as recording the time for one slugging cycle to complete .

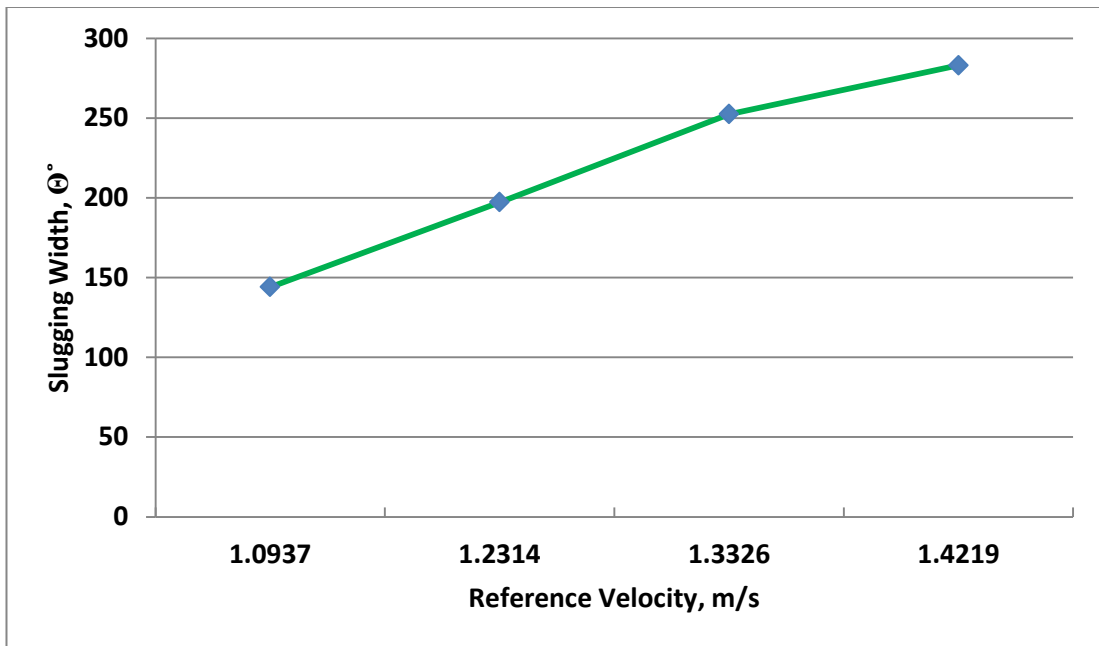


Figure 4.8: Slugging Width against Reference Velocity of 700g 4mm Spherical Particles

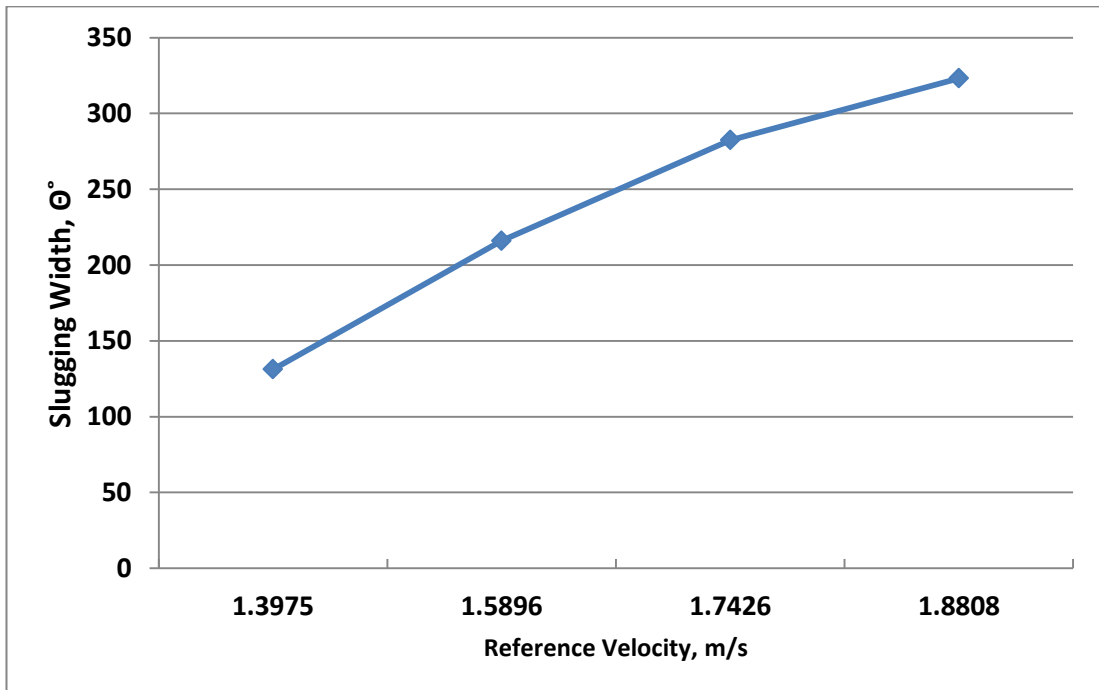


Figure 3: Slugging Width against Reference Velocity of 700g 5mm Spherical Particles

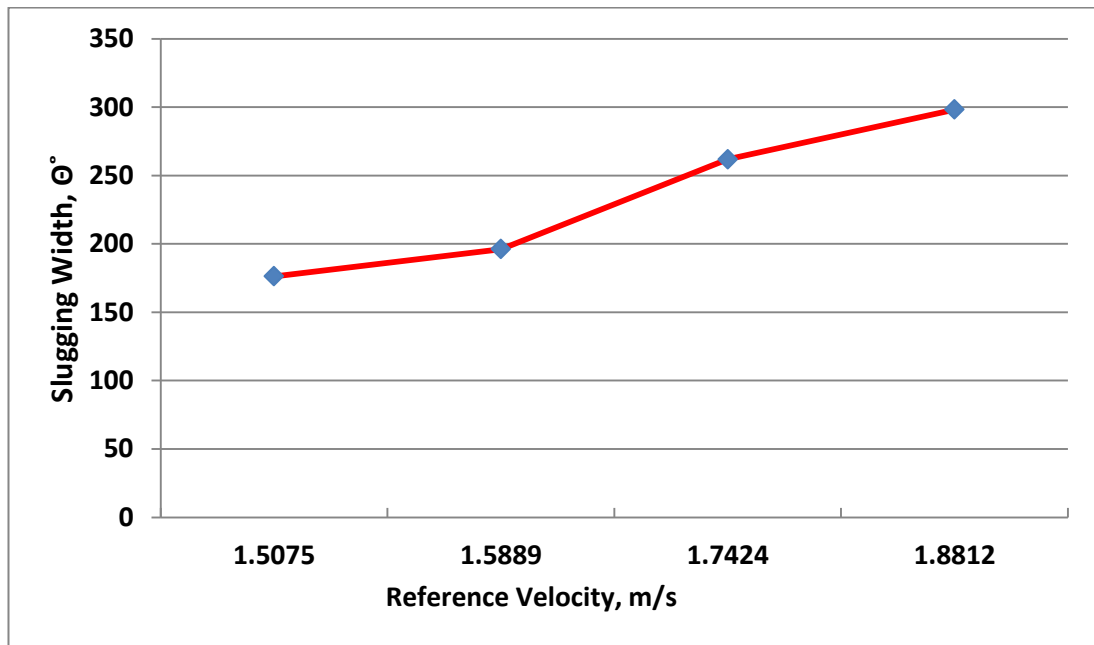


Figure 4.10: Slugging Width against Reference Velocity of 700g 6mm Spherical Particles

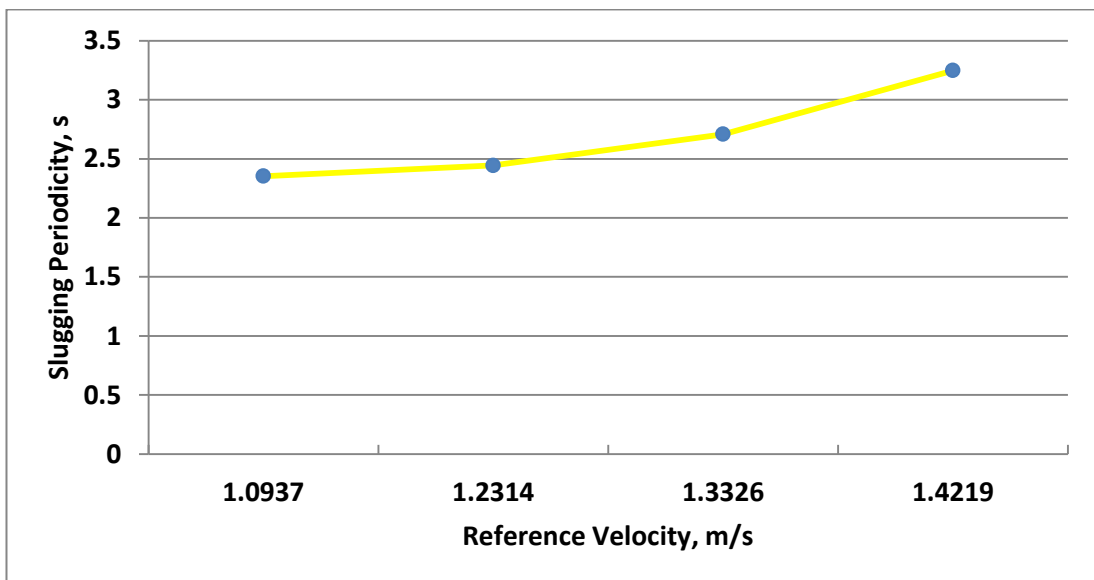


Figure 4.11: Slugging Periodicity against Reference Velocity of 700g 4mm Spherical Particles

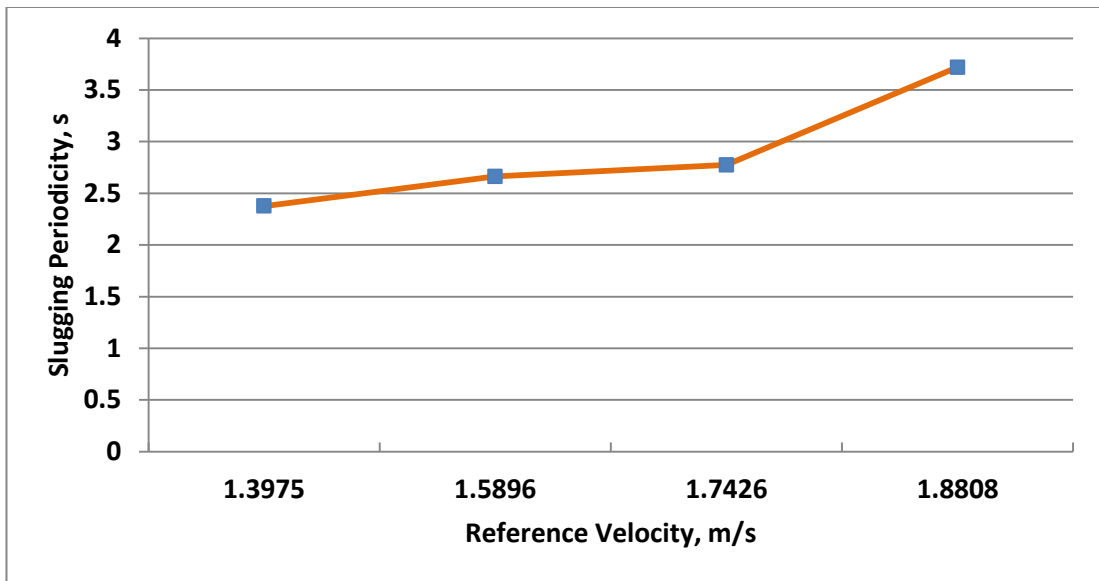


Figure 4.12: Slugging Periodicity against Reference Velocity of 700g 5mm Spherical Particles

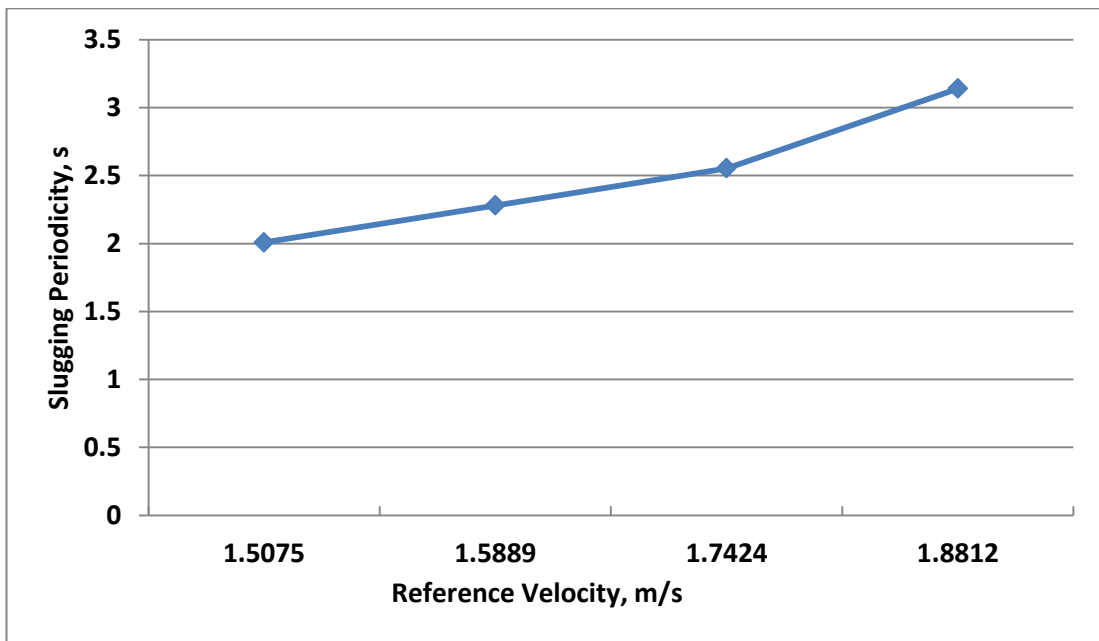


Figure 4.13: Slugging Periodicity against Reference Velocity of 700g 6mm Spherical Particles

From the Figure 4.8 to Figure 4.13, it can be seen that increasing reference velocity causes both slugging width and periodicity to increase. The reason behind this trend is because when reference velocity is higher, crest formation at the head of moving dune is higher. In addition, distance travelled is longer in order to compensate with the fading of crest formation. Moreover, the time to complete one slugging cycle is also increase with the reference velocity. To fade higher crest formation, it needs longer time, since the slugging width is also increased. To summarize the above reasoning, slugging distance travelled and crest deformation is proportional to the slugging time, where both of these characteristic are manipulated by reference velocity.

#### **4.6 Wavy Regime Timing**

Different types or particles and bed weights yields different slugging timing, which is the slugging start time and end time. In some cases, slugging starts and ends at lower reference velocity and some occurs at higher reference velocity. This study brings a major effect into practical use because in the industry, cost and time is the most important factor in their business. By figuring out the timing of starting and ending point of slugging under desired bed characteristic, it eases the company to perform better production, at the same time, saving cost and energy used. In author's experimental studies, he has come up with a comparison between bed loading and particles sizes and the relationship is shown at the Figure 4.14 and Figure 4.15.

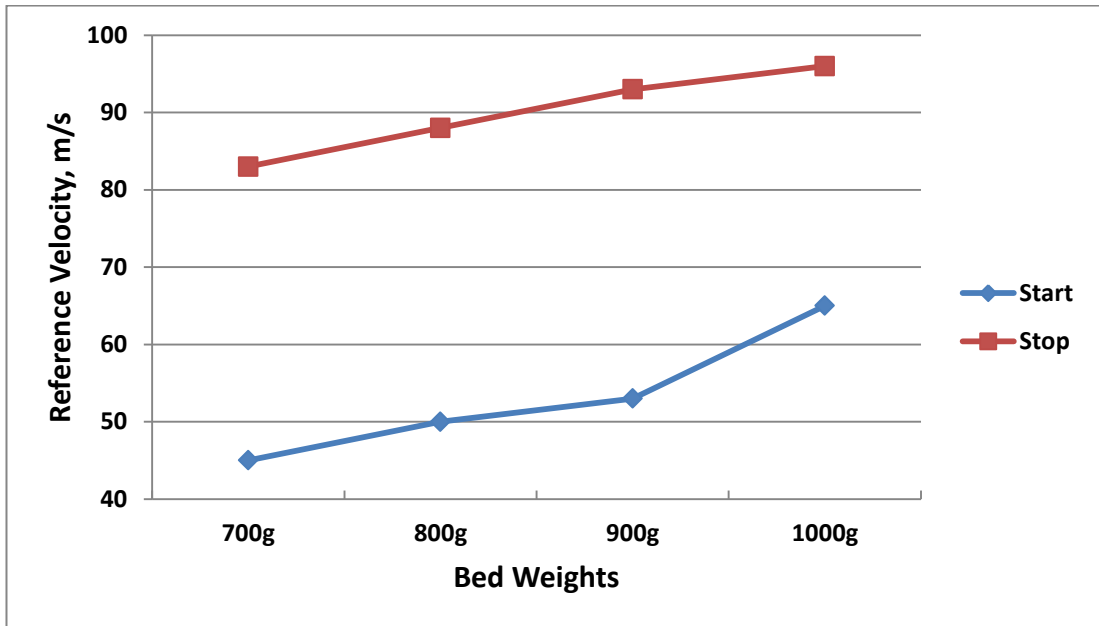


Figure 4.14: Reference Velocity against Bed Weights of 6mm Spherical Particles

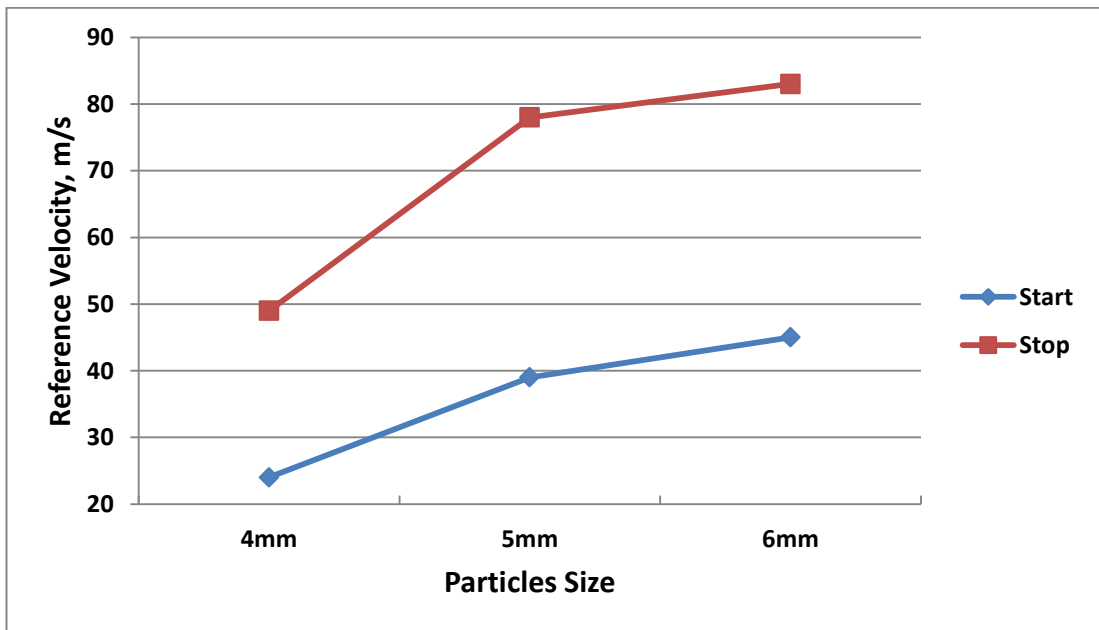


Figure 4.15: Reference Velocity against Different Size of Spherical Particles at 700g



#### **4.6.1 Bed Weights**

From Figure 4.14, smaller bed weights yields lower reference velocity to achieve slugging, and same goes to stop slugging whereas for higher bed loading, it behaves the other way round. The reason behind this trend is because lighter bed has smaller inertial force, so, lesser air is needed to fluidize the bed since the reacting force caused by the bed is small. Increase of bed weights will increase the bed resistance, as well as inertial forces. Bed resistance become a plus point because it can traps more air before the air escape from the bed. This can utilize most of the air energy to perform slugging and swirling activity, thus higher reference velocity is required. This is further proven by the large inertial force at large bed weights because reacting forces caused the bed is larger, so, more air is need to achieve slugging and swirling.

#### **4.6.2 Particle Size**

Figure 4.15 shows that smaller size particles at same bed weights require lower reference velocity to achieve start and end of slugging regime. In this case, smaller size particles have better surface area as compared to larger particles. The interstitial spaces are smaller, thus creating more bed resistance and air blockages for the air before escaping from the bed. This bed resistance turns to be an advantage for the bed to slug earlier because smaller particles which have higher bed resistance can trap more air and then, uses the kinetic energy to slug and swirl the bed. Throughout these studies, bed resistance can be an advantage or disadvantage, depending on the needs.

## CHAPTER 5

### Conclusion and Recommendation

As a conclusion, the aim of this project which is to create a comprehensive study of hydrodynamics for swirling fluidized bed, particularly relatively shallow beds has been achieved. Apart from that, the author also comes up with a research on slugging regime, which is the study of slugging width and slugging periodicity. Project Gantt chart and activity flow is done to act as a guideline for the author to deliver his task successfully within time frame.

Parameters were set and the author will be using spherical shape particles with diameter of 4mm, 5mm and 6mm. Blade inclination angle and overlapping angle will be set as 10° and 18° respectively. Bed weights starting from 300g is applicable for all particles shapes and increment of 100g bed weight throughout the experiment will be conducted until the end of slugging regime.

Experiments have been conducted using different particle size from 4mm to 6mm. Data is collected and graph is plotted to show the relationship between bed pressure drop and reference velocity. Few findings were obtained throughout the experiment; firstly, extremely shallow bed region is discovered. Secondly, larger particles have wider interstitial spaces, therefore creating more air passages. So, more amount of air is needed in order for fluidization to occur. Lastly, higher bed loading result in higher bed resistance thus requires bigger amount of air in order for fluidization to occur.

Besides that, slugging width and periodicity is found increasing with reference velocity, mainly due to bed resistance which causes difficulty for the air to escape from the bed. Next, slugging timing is studied as well at different particle sizes and bed weights to figure out when slugging starts and stops and hopefully this study can provide a good reference for the industry in maximizing their production.

Lastly, the author recommends that a proper camera setup should be installed at the lab equipment to ease video recording and taking picture when experimenting on slugging width in order obtain more accurate result. The author hopes that this research can bring positive outcome to the industry for better business growth.

## CHAPTER 6

### Bibliography

- [1] J.J. Goo, “Experimental Studies on the Hydrodynamics of Swirling Fluidized Bed,” BEng. dissertation, Dept. Mech. Eng., Universiti Teknologi PETRONAS, Perak, Malaysia, May 2012.
- [2] B. Sreenivasan and V.R. Raghavan, “Hydrodynamics of a Swirling Fluidized Bed”, Chemical Engineering and Processing, 2002, pp. 41, 99-106.
- [3] M. Faizal, K. V. Vinod and V.R. Raghavan, “Experimental Studies on a Swirling Fluidized Bed with Annular Distributor”, in Int. Conference on Plant, Equipment and Reliability, Kuala Lumpur, Malaysia, June 15-17 2010.
- [4] M.F.M. Batcha and V.R.Raghavan, “Experimental Studies on Swirling Fluidized Bed with Annular Distributor”, Journal of Applied Science 2011.
- [5] N. Fueyo and C. Dopazo, “Fluidization Fundamentals”, 1995, pp. 38-79.
- [6] S.Soponronnarit, “Fluidised Bed Grain Drying”, King Mongkut’s University of Technology Thonburi, 2003.
- [7] M. Faizal, M. Faiz, H. Salleh, H. Zakaria and V.R. Raghavan, “Drying of Oil Palm Frond via Swirling Fluidized Bed”, World Congress on Engineering 2011, July 6-8, 2011, London, U.K.
- [8] J.Shu, V.I. Lakshmanan, C.E. Dodson, “Hydrodynamics Study of a Toroidal Fluidized Bed Reactor”, Chemical Engineering and Processing, 2000, pp. 39, 499-506.
- [9] M.Faizal Mohideen, B. Screenivasan, Shaharin A.S and V.R. Raghavan, “Heat Transfer in a Swirling Fluidized Bed with Geldart type-D Particles”, Korean J. Chemical Engineering, 2 October 2011.
- [10] R. Kaewklum and V.I. Kuprianov, “Experimental Studies on Novel Swirling Fluidized Bed Combustor using an Annular Spiral Air Distributor”, 13 August 2009, pp.89.43-52.

- [11] V.I. Kuprianov, R. Kaewklum, KasamaSirisomboon, PorametArromdee and Songpol Chakritthakul, “Combustion and Emission Characteristics of a Swirling Fluidized Bed Combustor Burning Moisturized Rice Husk”, 9 October 2009, pp. 87, 2899-2906.
- [12] T. Madhiyanon, P. Sathitruangsak and S.Soponronnarit, “Combustion Characteristics of Rice-husk in a Short-Combustion-Chamber Fluidised-Bed Combustor (SFBC)”, Applied Thermal Engineering, 2010, pp. 30, 347-353.
- [13]M. M. Paulose, “Hydrodynamic Study of Swirling Fluidized Bed and The Role of Distributor”, School of Eng., Cochin University of Sci. and Technology, Kerala, India, 2006.
- [14] J. Paul C, “Influence of Angle of Air Injection and Particles in Bed Hydrodynamics of Swirling Fluidized Bed”, September 2008.
- [15] C. Sobrino, J.A. Almendros-Ibañez, D. Santana and M. de Vega, “Fluidization of Group B particles with a rotating distributor”, Powder Technology, 2007, pp. 181, 273–280.
- [16] S. Harish Kumar and D.V.R. Murthy, “Minimum Superficial Velocity in Gas-Solid Swirled Fluidized Bed”, 20 August 2010, pp49, 1095-1100.

## **APPENDICES**

**APPENDIX A** – Illustration of measuring Slugging Width and Flowchart of taking Slugging Period

**APPENDIX B** – Example of Reference Velocity Calculation

**APPENDIX C** – Project Recognition

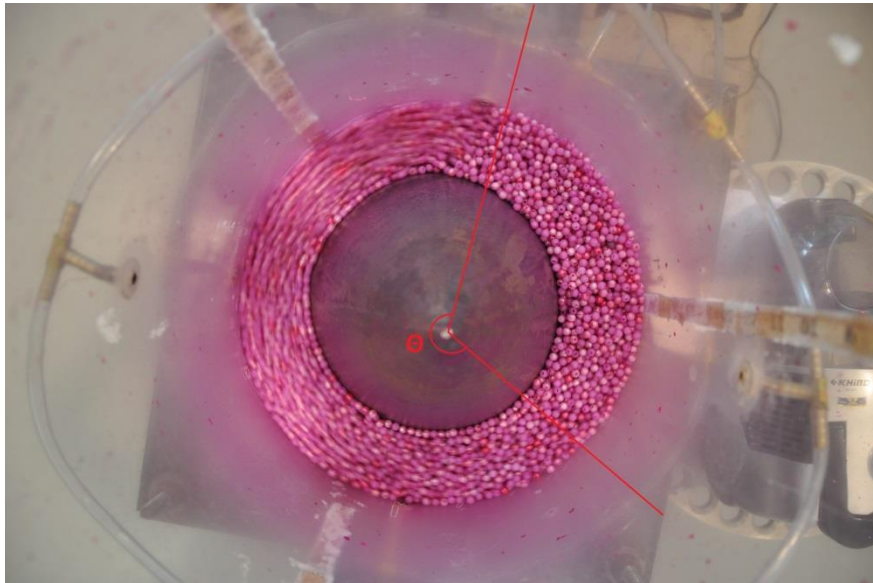
**APPENDIX D** – Experiment Raw Data

## CHAPTER 7

### APPENDICES

#### APPENDIX A - Illustration of measuring Slugging Width and Flowchart of taking Slugging Period

- i. **Example of slugging width measurement for 6mm spherical particles at bed weights of 800g**

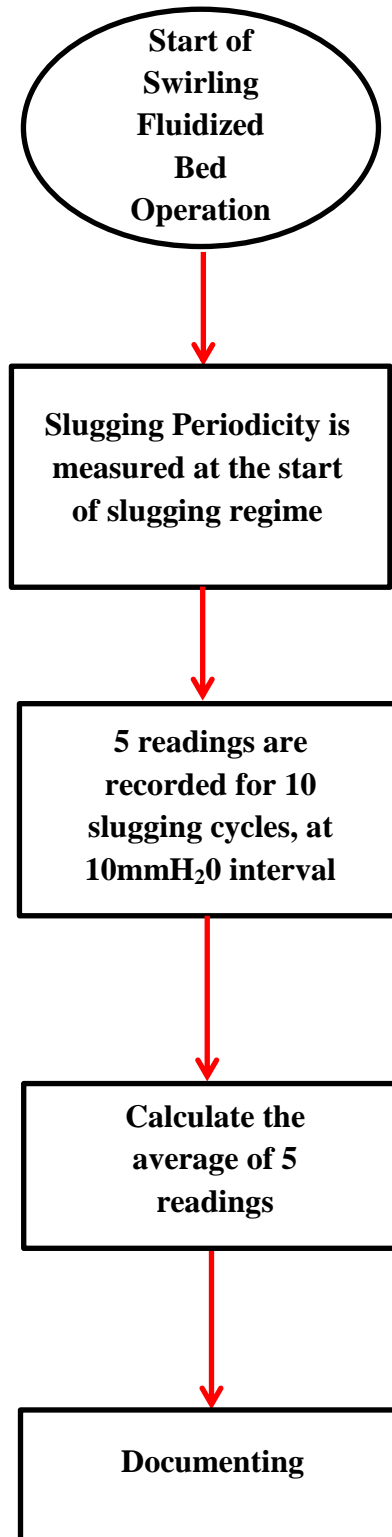


*Figure 7.1: Illustration of Slugging Width*

#### Procedure:

- i. When the bed reaches slugging regime, picture as illustrated above is taken at an increment of 10 mmH<sub>2</sub>O until the end of slugging regime.
- ii. Picture is analysed and lines are drawn to show the actual slugging width.
- iii. Protractor is used to measure the angle and data is recorded.
- iv. Steps above are repeated to get an average of 5 data for accuracy.
- v. Step 4 is repeated for every data collection.

ii. **Flow for measuring slugging periodicity**



## APPENDIX B – Example of Reference Velocity Calculation

### Formula

$$\text{Reference Velocity, } V_{\text{reference}} = \frac{\text{Air Flow Rate, } Q}{\text{Bed Area, } A_{\text{bed}}}$$

Air Flow Rate, Q

$$= \text{Orifice plate area, } A_o \times \text{Coefficient of discharge, } C_d \times \sqrt{\frac{2 \times g \left( \frac{\text{Pressure difference, } \Delta P}{\text{Air density, } \rho_{\text{air}}} \right)}{1 - (\text{Beta ratio, } \beta)^4}}$$

**Where,**

Orifice diameter hole,  $d = 0.062\text{m}$

Coefficient of discharge,  $C_d = 0.668$

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

Pipe diameter,  $D = 0.1\text{m}$

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

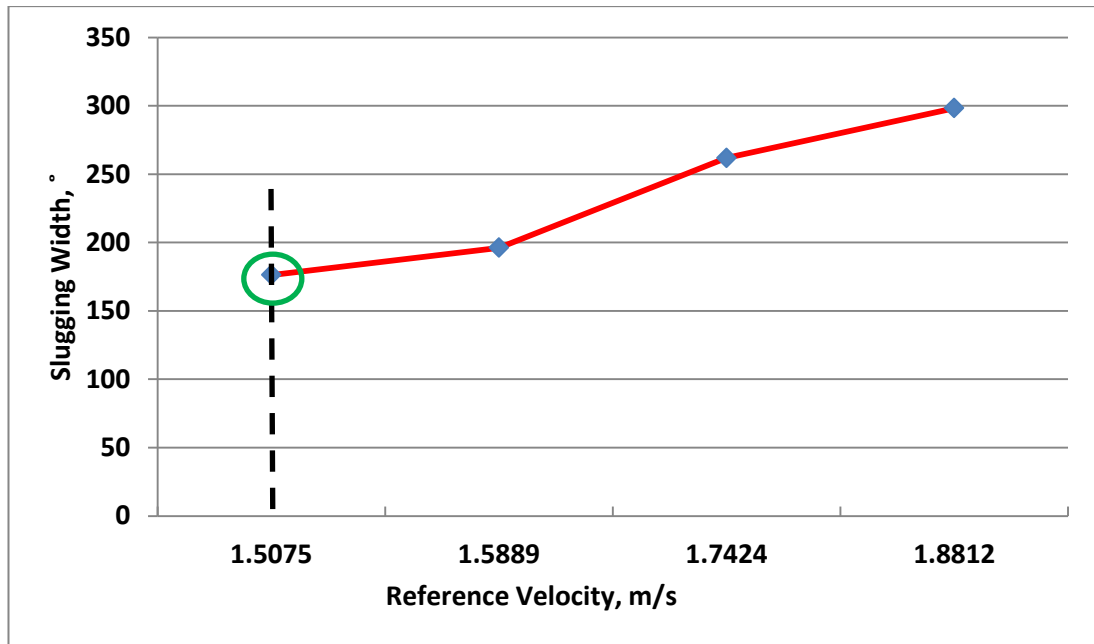
$$\text{Orifice plate area, } A_o = \frac{\pi \times d^2}{4} = \frac{\pi \times 0.062^2}{4} = 0.003019\text{m}^2$$

$$\begin{aligned} \text{Bed area} &= \frac{\pi}{4} (\text{Bed outer diameter, } d_o^2 - \text{Bed inner diameter, } d_i^2) \\ &= \frac{\pi}{4} (0.3^2 - 0.2^2) \\ &= 0.03927\text{m}^2 \end{aligned}$$

$$\begin{aligned} V_{\text{reference}} &= \frac{0.003019 \times 0.668 \times \sqrt{2 \times 9.81 \times \left( \frac{\text{Pressure difference, } \Delta P}{1.2} \right)}}{0.03927} \\ &= \underline{\underline{0.2249 \sqrt{\text{Pressure difference, } \Delta P}}} \end{aligned}$$

\*The calculation of  $V_{\text{reference}}$  here is the same as calculation of  $V_{\text{superficial}}$  in the references referred to\*





*Figure 7.2: Slugging Width against Reference Velocity of 700g 6mm Spherical Particles*

At the circle point,

Pressure drop across orifice plate is at 44.93 mmH<sub>2</sub>O (reading from pressure transmitter),

$$V_{reference} = 0.2249 \sqrt{\text{Pressure Difference at Orifice, } \Delta P}$$

$$V_{reference} = 0.2249 \sqrt{45}$$

$$= \underline{\underline{1.5075 \text{ m/s}}}$$

## APPENDIX C – Project Recognition

### 2013 3rd International Conference on Advanced Design and Manufacturing Engineering

July 13-14, Anshan, China

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#### Notification of Paper Acceptance

Dear Authors,

The scientific committee has completed its review of your paper submitted for International Conference on Advanced Design and Manufacturing Engineering (ADME 2013). The final decision is made base on the peer-review reports, the scientific merits and the relevance.

We are pleased to inform you that your paper as follow has now been accepted by the scientific committee and will be published in international journal "Applied Mechanics and Materials", and will be indexed by EI COMPENDEX, SCOPUS and Thomson ISTP.

Manuscript Number	LN3372
Authors	Tan Yinn Sern, Chin Yee Sing
Title	Experimental Studies on Wavy Regime in Swirling Fluidized Bed

Notes:

1. Please revise your manuscript according to the detailed comments and suggestions from the referees. And make sure that your paper is in strict accordance with the format of the journal.
2. Please read the attached registration form carefully and make sure that you pay the registration fees in time.

Any questions, please do not hesitate to contact us.

The Comm  ICADME 2013  
Hong Kong Industrial Techno  Research Centre

2013-7-5

*Figure 7.3: Technical paper accepted by ICADME 2013*

**2013 3rd International Conference on  
Chemical Engineering and Advanced Materials  
July 6-7, Guangzhou, China**

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**Notification of Paper Acceptance**

**Dear Authors,**

The Scientific Committee has completed its review of your paper submitted for the 2013 3rd International Conference on Chemical Engineering and Advanced Materials (CEAM 2013). The final decision is made base on the peer-review reports, the scientific merits and the relevance.

We are pleased to inform you that your paper as follow has now been accepted by the Scientific Committee of CEAM 2013 and will be published in international journal "Advanced Materials Research", and will be indexed by EI COMPENDEX and Thomson ISTP.

Manuscript Number	CM2707
Authors	Tan Yinn Sern, Chin Yee Sing
Title	Experimental Study on Wavy Regime in Swirling Fluidized Bed

Notes:

1. Please revise your manuscript according to the detailed comments and suggestions from the referees. And make sure that your paper is in strict accordance with the format of the journal.
2. Please read the attached registration form carefully and make sure that you pay the registration fees in time.

Any questions, please do not hesitate to contact us.

The Scientific Committee of CEAM 2013  
Hong Kong Industrial Technology Research Centre



2013-5-28

*Figure 7.4: Technical paper accepted by ICCEAM 2013*

## APPENDIX D- Experiment Raw Data

### 4mm Particles

Shape: Spherical		Size: 4mm		Mass: 300g		Inclination: 10deg		Overlap: 18deg										
Data No.	$\Delta P$ across orifice	Reference Velocity	$\Delta P$ across distributor	$\Delta P$ across distributor with particle	$\Delta P$ across bed	Slugging Width					Slugging Period					Observation		
	mm $H_2O$	m/s	mm $H_2O$	mm $H_2O$	mm $H_2O$	$W_1$	$W_2$	$W_3$	$W_4$	$W_5$	Avg	$T_1$	$T_2$	$T_3$	$T_4$		$T_5$	Avg
		0			0													
	5.03	0.5044	4.21	10.51	6.3													Packed
	9.95	0.7094	7.51	13.95	6.44													Incipient
	14.39	0.8531	10.33	16.45	6.12													Start Slugging
	15.07	0.8731	10.71	16.79	6.08													Slugging
	19.95	1.0045	13.72	19.98	6.26													Slugging
	25.13	1.1274	16.86	23.22	6.36													Slugging
	28.53	1.2013	18.98	25.24	6.26	<b>Extremely Shallow Bed</b>												Stop Slugging
	30.13	1.2345	19.58	26.23	6.65													Swirling
	35.04	1.3313	22.66	29.13	6.47													Swirling
	39.93	1.4211	25.53	31.93	6.4													Swirling
	50.09	1.5917	31.72	37.76	6.04													Swirling
	59.84	1.7397	37.54	43.72	6.18													Swirling
	70.04	1.8822	43.32	50.05	6.73													Swirling
	80.13	2.0132	49.29	56.56	7.27													Swirling + Minor Entrainment
	90.14	2.1352	54.72	62.41	7.69													Swirling + Minor Entrainment
	99.85	2.2473	61.02	68.41	7.39													Entrainment

Shape: Spherical		Size: 4mm		Mass: 400g		Inclination: 10deg		Overlap: 18deg										
Data No.	$\Delta P$ across orifice mm $H_2O$	Reference Velocity m/s	$\Delta P$ across distributor mm $H_2O$	$\Delta P$ across distributor with particle mm $H_2O$	$\Delta P$ across bed mm $H_2O$	Slugging Width					Slugging Period					Observation		
						$W_1$ Ø	$W_2$ Ø	$W_3$ Ø	$W_4$ Ø	$W_5$ Ø	Avg Ø	$T_1$ sec	$T_2$ sec	$T_3$ sec	$T_4$ sec		$T_5$ sec	Avg sec
		0			0													
	5.02	0.5039	4.21	8.64	4.43													Packed
	10.06	0.7133	7.51	15.25	7.74													Packed
	14.95	0.8696	10.71	19.34	8.63													Incipient
	16.32	0.9086	11.59	20.03	8.44													Start Slugging
	19.86	1.0023	13.72	22.05	8.33													Slugging
	25.16	1.1281	16.86	25.24	8.38													Slugging
	30.06	1.2331	19.58	28.41	8.83													Slugging
	32.94	1.2908	21.72	29.97	8.25													Stop Slugging
	40.07	1.4236	25.53	34.38	8.85													Swirling
	50.11	1.5920	31.72	40.42	8.7													Swirling
	60.07	1.7431	37.54	46.38	8.84													Swirling
	70.09	1.8829	43.32	52.41	9.09													Swirling
	80.14	2.0133	49.29	59.03	9.74													Swirling
	90.13	2.1351	54.72	64.95	10.23													Swirling + Minor Entrainment
	100.16	2.2508	61.02	71.07	10.05													Swirling + Minor Entrainment
	110.12	2.3601	66.36	77.14	10.78													Entrainment

**Extremely Shallow Bed**

Shape: Spherical		Size: 4mm		Mass: 500g		Inclination: 10deg		Overlap: 18deg										
Data No.	$\Delta P$ across orifice mm $H_2O$	Reference Velocity m/s	$\Delta P$ across distributor mm $H_2O$	$\Delta P$ across distributor with particle mm $H_2O$	$\Delta P$ across bed mm $H_2O$	Slugging Width					Slugging Period					Observation		
						$W_1$ Ø	$W_2$ Ø	$W_3$ Ø	$W_4$ Ø	$W_5$ Ø	Avg Ø	$T_1$ sec	$T_2$ sec	$T_3$ sec	$T_4$ sec		$T_5$ sec	Avg sec
		0			0													
	5.01	0.5034	4.21	9.37	5.16													Packed
	10.05	0.7130	7.51	16.55	9.04													Packed
	15.06	0.8728	10.71	21.36	10.65													Incipient
	17.48	0.9403	12.25	22.62	10.37	105	110	98	108	112	106.6	2.904	2.865	2.866	2.879	2.869	2.877	Start Slugging
	25.08	1.1263	16.86	27.31	10.45	200	193	186	200	210	197.8	3.007	3.043	3.039	3.024	3.011	3.025	Slugging
	30.03	1.2324	19.58	30.32	10.74	231	232	218	243	255	235.8	3.022	3.061	3.035	3.034	3.035	3.037	Slugging
	38.03	1.3869	24.61	35.16	10.55													Stop Slugging
	45.09	1.5102	28.73	39.62	10.89													Swirling
	50.13	1.5923	31.72	42.68	10.96													Swirling
	60.04	1.7426	37.54	48.94	11.4													Swirling
	70.13	1.8834	43.32	55.31	11.99													Swirling (see blades)
	79.93	2.0107	49.29	61.21	11.92													Swirling (see blades)
	90.11	2.1349	54.72	67.44	12.72													Swirling (see blades)
	99.89	2.2478	61.02	73.31	12.29													Swirling (see blades) + Minor Entrainment
	110.17	2.3606	66.36	79.94	13.58													Swirling (see blades) + Minor Entrainment
	120.14	2.4651	72.84	86.14	13.3													Entrainment

Shape: Spherical		Size: 4mm		Mass: 600g		Inclination: 10deg		Overlap: 18deg											
Data No.	$\Delta P$ across orifice	Reference Velocity	$\Delta P$ across distributor	$\Delta P$ across distributor with particle	$\Delta P$ across bed	Slugging Width						Slugging Period					Observation		
	mm $H_2O$	m/s	mm $H_2O$	mm $H_2O$	mm $H_2O$	$W_1$	$W_2$	$W_3$	$W_4$	$W_5$	Avg	$T_1$	$T_2$	$T_3$	$T_4$	$T_5$		Avg	
						0	0	0	0	0	0								
4.97	0.5014		4.21	10.88	6.67													Packed	
10.02	0.7119		7.51	19.43	11.92													Packed	
15.06	0.8728		10.71	24.22	13.51													Incipient	
18.44	0.9658		12.81	26.31	13.5	68	74	78	82	65	73.4	2.479	2.481	2.457	2.467	2.449	2.467	Start Slugging	
24.94	1.1231		16.86	30.09	13.23	190	171	172	164	166	172.6	2.739	2.749	2.751	2.748	2.739	2.745	Slugging	
30.07	1.2333		19.58	33.17	13.59	200	213	222	201	205	208.2	2.752	2.767	2.757	2.754	2.766	2.759	Slugging	
34.97	1.3300		22.66	36.08	13.42	264	283	262	277	268	270.8	3.222	3.198	3.181	3.173	3.191	3.193	Slugging	
43.28	1.4796		27.58	40.77	13.19													Stop Slugging	
50.08	1.5916		31.72	45.03	13.31													Swirling	
59.98	1.7418		37.54	50.81	13.27													Swirling	
69.93	1.8807		43.32	57.16	13.84													Swirling	
79.85	2.0097		49.29	63.48	14.19													Swirling (see blades)	
89.94	2.1329		54.72	70.06	15.34													Swirling (see blades)	
99.88	2.2477		61.02	75.78	14.76													Swirling (see blades)	
110.13	2.3602		66.36	81.57	15.21													Swirling (see blades) + Minor Entrainment	
120.12	2.4649		72.84	87.66	14.82													Swirling (see blades) + Minor Entrainment	
129.98	2.5641		78.14	93.13	14.99													Entrainment	
140.03	2.6613		83.24	99.14	15.9													Entrainment	

Shape: Spherical		Size: 4mm		Mass: 700g		Inclination: 10deg		Overlap: 18deg											
Data No.	$\Delta P$ across orifice	Reference Velocity	$\Delta P$ across distributor	$\Delta P$ across distributor with particle	$\Delta P$ across bed	Slugging Width						Slugging Period					Observation		
	mm $H_2O$	m/s	mm $H_2O$	mm $H_2O$	mm $H_2O$	$W_1$	$W_2$	$W_3$	$W_4$	$W_5$	Avg	$T_1$	$T_2$	$T_3$	$T_4$	$T_5$		Avg	
						0	0	0	0	0	0								
5.02	0.5039		4.21	11.34	7.13													Packed	
10.03	0.7123		7.51	20.17	12.66													Packed	
15.07	0.8731		10.71	26.45	15.74													Incipient	
19.96	1.0048		13.72	29.12	15.4													Incipient	
23.65	1.0937		16.09	31.53	15.44	150	129	142	161	138	144	2.379	2.342	2.351	2.354	2.336	2.352	Start Slugging	
29.98	1.2314		19.58	35.04	15.46	191	208	199	200	188	197.2	2.441	2.436	2.429	2.457	2.455	2.444	Slugging	
35.11	1.3326		22.66	38.16	15.5	226	267	266	251	252	252.4	2.717	2.711	2.727	2.702	2.681	2.708	Slugging	
39.97	1.4219		23.53	40.86	17.33	300	294	262	290	269	283	3.199	3.261	3.276	3.234	3.271	3.248	Slugging	
48.63	1.5683		30.82	46.17	15.35													Stop Slugging	
60.07	1.7431		37.54	53.09	15.55													Swirling	
70.04	1.8822		43.32	59.03	15.71													Swirling	
79.96	2.0111		49.29	66.12	16.83													Swirling (see blades)	
90.05	2.1342		54.72	71.94	17.22													Swirling (see blades)	
100.09	2.2500		61.02	78.89	17.87													Swirling (see blades)	
110.13	2.3602		66.36	84.07	17.71													Swirling (see blades) + Minor Entrainment	
119.98	2.4635		72.84	90.08	17.24													Swirling (see blades) + Minor Entrainment	
130.14	2.5656		78.14	95.29	17.15													Entrainment	
140.07	2.6617		83.24	101.33	18.09													Entrainment	
150.11	2.7555		89.83	107.55	17.72													Entrainment	

Shape: Spherical		Size: 4mm		Mass: 800g		Inclination: 10deg		Overlap: 18deg																				
Data No.	$\Delta P$ across orifice	Reference Velocity	$\Delta P$ across distributor	$\Delta P$ across distributor with particle	$\Delta P$ across bed	Slugging Width						Slugging Period					Observation											
	mm $H_2O$	m/s	mm $H_2O$	mm $H_2O$	mm $H_2O$	$W_1$	$W_2$	$W_3$	$W_4$	$W_5$	Avg	$T_1$	$T_2$	$T_3$	$T_4$	$T_5$		Avg										
						$\ominus$	$\ominus$	$\ominus$	$\ominus$	$\ominus$	$\ominus$	sec	sec	sec	sec	sec	sec											
		0																										
	9.96	0.7098	7.51	21.96	14.45																							Packed
	15.01	0.8713	10.71	28.27	17.56																							Incipient
	20.07	1.0075	13.72	31.07	17.35																							Incipient
	21.82	1.0506	14.83	32.25	17.42																							Start two layer
	25.06	1.1258	16.86	33.96	17.1																							Two layer + minor bubble
	29.97	1.2312	19.58	36.61	17.03																							Two layer + minor bubble
	34.94	1.3294	22.66	39.72	17.06																							Slugging + Two Layer + minor bubble
	40.07	1.4236	25.53	42.48	16.95																							Slugging + Two Layer + minor bubble
	50.11	1.5920	31.72	48.81	17.09																							Minor Slugging + Two Layer + bubble
	60.07	1.7431	37.54	55.02	17.48																							Bubbling + swirling
	69.97	1.8812	43.32	60.98	17.66																							Bubbling + swirling
	79.92	2.0106	49.29	67.56	18.27																							Bubbling + swirling
	90.06	2.1343	54.72	73.82	19.1																							Start Entrainment
	100.02	2.2492	61.02	79.92	18.9																							Entrainment
	110.06	2.3594	66.36	86.12	19.76																							Entrainment

**Two Layer**

### 5mm Particles

Shape: Spherical		Size: 5mm		Mass: 300g		Inclination: 10deg		Overlap: 18deg																						
Data No.	$\Delta P$ across orifice	Reference Velocity	$\Delta P$ across distributor	$\Delta P$ across distributor with particle	$\Delta P$ across bed	Slugging Width						Slugging Period					Observation													
	mm $H_2O$	m/s	mm $H_2O$	mm $H_2O$	mm $H_2O$	$W_1$	$W_2$	$W_3$	$W_4$	$W_5$	Avg	$T_1$	$T_2$	$T_3$	$T_4$	$T_5$		Avg												
						$\ominus$	$\ominus$	$\ominus$	$\ominus$	$\ominus$	$\ominus$	sec	sec	sec	sec	sec	sec													
		0																												
	4.96	0.5009	4.21	7.13	2.92																								Packed	
	9.98	0.7105	7.51	12.95	5.44																								Packed	
	14.97	0.8702	10.71	17.58	6.87																								Packed	
	20.01	1.0060	13.72	19.67	5.95																								Incipient	
	23.01	1.0788	15.61	20.67	5.06																								Start slugging	
	25.04	1.1254	16.86	22.14	5.28																								Slugging	
	29.97	1.2312	19.58	25.09	5.51																								Slugging	
	35.04	1.3313	22.66	28.23	5.57																								Slugging	
	39.94	1.4213	25.53	31.52	5.99																								Slugging	
	43.02	1.4751	27.73	33.36	5.63																								Stop Slugging	
	49.94	1.5893	31.72	37.78	6.06																								Swirling	
	60.06	1.7429	37.54	43.77	6.23																								Fully Swirling	
	70.03	1.8821	43.32	49.53	6.21																								Fully Swirling	
	79.98	2.0113	49.29	56.12	6.83																								Fully Swirling	
	90.12	2.1350	54.72	61.95	7.23																								Fully Swirling	
	100.07	2.2498	61.02	68.03	7.01																								Fully Swirling	
	109.94	2.3581	66.36	74.24	7.88																								Minor Entrainment	
	120.08	2.4645	72.84	80.86	8.02																								Entrainment	

**Extremely Shallow Bed**

Shape: Spherical		Size: 5mm		Mass: 400g		Inclination: 10deg		Overlap: 18deg										
Data No.	$\Delta P$ across orifice mm $H_2O$	Reference Velocity m/s	$\Delta P$ across distributor mm $H_2O$	$\Delta P$ across distributor with particle mm $H_2O$	$\Delta P$ across bed mm $H_2O$	Slugging Width						Slugging Period					Observation	
						$W_1$ Ø	$W_2$ Ø	$W_3$ Ø	$W_4$ Ø	$W_5$ Ø	Avg Ø	$T_1$ sec	$T_2$ sec	$T_3$ sec	$T_4$ sec	$T_5$ sec		Avg sec
		0			0													
	10.01	0.7116	7.51	12.78	5.27													Packed
	19.95	1.0045	13.72	22.76	9.04													Packed
	25.03	1.1252	16.86	24.97	8.11													Incipient
	28.74	1.2057	18.95	26.38	7.43													Start Slugging
	34.92	1.3290	22.66	30.32	7.66													Slugging
	40.05	1.4233	25.53	33.55	8.02													Slugging
	45.03	1.5092	28.73	36.59	7.86													Slugging
	53.36	1.6428	33.85	41.42	7.57													Stop Slugging
	59.97	1.7416	37.54	45.81	8.27													Swirling
	69.94	1.8808	43.32	51.52	8.2													Fully Swirling
	80.02	2.0118	49.29	57.55	8.26													Fully Swirling
	89.96	2.1331	54.72	63.28	8.56													Fully Swirling
	100.12	2.2503	61.02	69.18	8.16													Fully Swirling
	110.04	2.3592	66.36	76.03	9.67													Fully Swirling
	119.94	2.4630	72.84	81.75	8.91													Fully Swirling
	130.09	2.5651	78.14	87.93	9.79													Fully Swirling
	140.13	2.6623	83.24	93.57	10.33													Minor Entrainment
	150.05	2.7549	89.83	100.03	10.2													Minor Entrainment
	160.04	2.8451	95.66	105.98	10.32													Entrainment

**Extremely Shallow Bed**

Shape: Spherical		Size: 5mm		Mass: 500g		Inclination: 10deg		Overlap: 18deg										
Data No.	$\Delta P$ across orifice mm $H_2O$	Reference Velocity m/s	$\Delta P$ across distributor mm $H_2O$	$\Delta P$ across distributor with particle mm $H_2O$	$\Delta P$ across bed mm $H_2O$	Slugging Width						Slugging Period					Observation	
						$W_1$ Ø	$W_2$ Ø	$W_3$ Ø	$W_4$ Ø	$W_5$ Ø	Avg Ø	$T_1$ sec	$T_2$ sec	$T_3$ sec	$T_4$ sec	$T_5$ sec		Avg sec
		0			0													
	10.02	0.7119	7.51	13.24	5.73													Packed
	20.05	1.0070	13.72	24.08	10.36													Packed
	29.95	1.2308	19.58	30.28	10.7													Start slugging
	35.05	1.3315	22.66	33.23	10.57													Slugging
	39.94	1.4213	25.53	36.25	10.72													Slugging
	45.02	1.5090	28.73	39.18	10.45													Slugging
	49.97	1.5898	31.72	42.02	10.3													Slugging
	56.61	1.6921	35.73	46.45	10.72													Stop Slugging
	69.96	1.8811	43.32	54.46	11.14													Fully Swirling
	80.09	2.0127	49.29	61.07	11.78													Fully Swirling
	90.08	2.1345	54.72	67.17	12.45													Fully Swirling
	99.98	2.2488	61.02	73.31	12.29													Fully Swirling
	109.93	2.3580	66.36	79.11	12.75													Fully Swirling
	119.95	2.4631	72.84	85.19	12.35													Fully Swirling
	130.09	2.5651	78.14	91.12	12.98													Fully Swirling
	139.94	2.6605	83.24	97.23	13.99													Fully Swirling
	150.04	2.7548	89.83	103.58	13.75													Fully Swirling
	160.12	2.8459	95.66	109.82	14.16													Fully Swirling
	170.11	2.9333	101.14	116.18	15.04													Minor Entrainment
	180.09	3.0181	106.72	122.21	15.49													Minor Entrainment
	190.07	3.1006	112.84	128.73	15.89													Entrainment

**Extremely Shallow Bed**





Shape: Spherical		Size: 5mm		Mass: 800g		Inclination: 10deg		Overlap: 18deg											
Data No.	ΔP across orifice mm H <sub>2</sub> O	Reference Velocity m/s	ΔP across distributor mm H <sub>2</sub> O	ΔP across distributor with particle mm H <sub>2</sub> O	ΔP across bed mm H <sub>2</sub> O	Slugging Width					Slugging Period					Observation			
						W <sub>1</sub> ∅	W <sub>2</sub> ∅	W <sub>3</sub> ∅	W <sub>4</sub> ∅	W <sub>5</sub> ∅	Avg ∅	T <sub>1</sub> sec	T <sub>2</sub> sec	T <sub>3</sub> sec	T <sub>4</sub> sec		T <sub>5</sub> sec	Avg sec	
			0																
9.99		0.7108	7.51	15.21	7.7														Packed
20.03		1.0065	13.72	27.63	13.91														Packed
29.95		1.2308	19.58	37.08	17.5														Incipient
40.06		1.4235	25.53	43.26	17.73														Incipient
45.12		1.5107	28.73	46.16	17.43	144	118	99	125	125	122.2	2.107	2.094	2.111	2.085	2.081	2.096	Start Slugging	
59.96		1.7415	37.54	54.27	16.73	246	230	223	230	216	229	2.473	2.504	2.464	2.475	2.464	2.476	Slugging	
70.08		1.8827	43.32	60.46	17.14	295	295	275	295	280	288	3.087	3.064	3.064	3.057	3.051	3.065	Slugging	
75.07		1.9486	46.31	63.32	17.01	321	317	321	335	330	324.8	3.824	3.794	3.737	3.765	3.813	3.787	Slugging	
83.13		2.0505	51.17	68.91	17.74														Stop Slugging
89.96		2.1331	54.72	72.83	18.11														Swirling
99.95		2.2484	61.02	78.93	17.91														Swirling
110.05		2.3593	66.36	85.21	18.85														Fully Swirling
119.91		2.4627	72.84	91.28	18.44														Fully Swirling
130.04		2.5646	78.14	97.07	18.93														Fully Swirling
140.11		2.6621	83.24	103.03	19.79														Fully Swirling
150.08		2.7552	89.83	109.35	19.52														Fully Swirling
160.06		2.8453	95.66	115.31	19.65														Fully Swirling
170.08		2.9330	101.14	121.58	20.44														Fully Swirling
180.02		3.0175	106.72	127.54	20.82														Fully Swirling
189.93		3.0995	112.84	133.43	20.59														Fully Swirling
200.07		3.1811	118.25	139.22	20.97														Fully Swirling
209.92		3.2585	124.65	145.84	21.19														Minor Entrainment
220.09		3.3365	130.72	151.65	20.93														Minor Entrainment
229.88		3.4099	136.55	158.63	22.08														Minor Entrainment
239.89		3.4833	142.07	165.28	23.21														Entrainment

Shape: Spherical		Size: 5mm		Mass: 900g		Inclination: 10deg		Overlap: 18deg												
Data No.	ΔP across orifice mm H <sub>2</sub> O	Reference Velocity m/s	ΔP across distributor mm H <sub>2</sub> O	ΔP across distributor with particle mm H <sub>2</sub> O	ΔP across bed mm H <sub>2</sub> O	Slugging Width					Slugging Period					Observation				
						W <sub>1</sub> ∅	W <sub>2</sub> ∅	W <sub>3</sub> ∅	W <sub>4</sub> ∅	W <sub>5</sub> ∅	Avg ∅	T <sub>1</sub> sec	T <sub>2</sub> sec	T <sub>3</sub> sec	T <sub>4</sub> sec		T <sub>5</sub> sec	Avg sec		
			0																	
9.99		0.7108	7.51	15.48	7.97															Packed
19.97		1.0050	13.72	28.12	14.4															Packed
29.98		1.2314	19.58	40.07	20.49															Packed
39.95		1.4215	25.53	45.36	19.83															Incipient
50.09		1.5917	31.72	51.33	19.61	140	154	160	120	105	135.8	1.991	1.961	1.957	1.957	1.948	1.963	Start Slugging		
60.02		1.7424	37.54	56.96	19.42	200	200	245	202	218	213	2.237	2.238	2.215	2.231	2.221	2.228	Slugging		
70.03		1.8821	43.32	62.57	19.25	298	300	304	310	306	303.6	2.651	2.661	2.651	2.641	2.627	2.646	Slugging		
75.04		1.9482	46.31	65.83	19.52	317	310	333	320	322	320.4	3.154	3.123	3.111	3.161	3.131	3.136	Slugging		
86.95		2.0971	53.52	72.77	19.25															Stop Slugging
100.05		2.2496	61.02	81.38	20.36															Swirling
109.97		2.3584	66.36	87.53	21.17															Swirling
120.06		2.4643	72.84	93.54	20.7															Fully Swirling
130.08		2.5650	78.14	99.58	21.44															Fully Swirling
139.93		2.6604	83.24	105.43	22.19															Fully Swirling
149.88		2.7533	89.83	112.33	22.5															Fully Swirling
160.15		2.8461	95.66	118.54	22.88															Fully Swirling
170.03		2.9326	101.14	125.08	23.94															Fully Swirling
180.13		3.0184	106.72	131.42	24.7															Fully Swirling
190.07		3.1006	112.84	137.55	24.71															Minor Entrainment
200.11		3.1814	118.25	143.23	24.98															Minor Entrainment
210.07		3.2597	124.65	150.17	25.52															Entrainment
220.06		3.3363	130.72	160.08	29.36															Entrainment

Shape: Spherical		Size: 5mm		Mass: 1000g		Inclination: 10deg		Overlap: 18deg											
Data No.	$\Delta P$ across orifice mm $H_2O$	Reference Velocity m/s	$\Delta P$ across distributor mm $H_2O$	$\Delta P$ across distributor with particle mm $H_2O$	$\Delta P$ across bed mm $H_2O$	Slugging Width						Slugging Period					Observation		
						$W_1$ Ø	$W_2$ Ø	$W_3$ Ø	$W_4$ Ø	$W_5$ Ø	Avg Ø	$T_1$ sec	$T_2$ sec	$T_3$ sec	$T_4$ sec	$T_5$ sec		Avg sec	
		0			0														
	9.98	0.7105	7.51	15.74	8.23													Packed	
	20.01	1.0060	13.72	28.83	15.11													Packed	
	30.03	1.2324	19.58	41.12	21.54													Packed	
	40.05	1.4233	25.53	47.86	22.33													Incipient	
	50.03	1.5908	31.72	53.58	21.86													Start of Two Layer	
	60.03	1.7425	37.54	59.38	21.84													Two Layer + Slugging + Minor Bubble	
	69.95	1.8810	43.32	65.72	22.4													Two Layer + Slugging + Minor Bubble	
	79.97	2.0112	49.29	71.78	22.49													Two Layer + Swirling + Minor Bubble	
	90.04	2.1341	54.72	78.14	23.42													Two Layer + Swirling + Minor Bubble	
	100.13	2.2505	61.02	84.25	23.23													Two Layer + Swirling + Minor Bubble	
	110.03	2.3591	66.36	90.88	24.52													Two Layer + Swirling + Minor Bubble	
	119.95	2.4631	72.84	97.12	24.28													Two Layer + Swirling + Bubble	
	130.11	2.5653	78.14	102.51	24.37													Two Layer + Swirling + Bubble	
	139.96	2.6607	83.24	108.93	25.69													Two Layer + Swirling + Bubble	
	150.07	2.7551	89.83	115.66	25.83													Two Layer + Swirling + Bubble	
	159.93	2.8442	95.66	122.15	26.49													Two Layer + Swirling + Bubble	
	170.07	2.9329	101.14	128.89	27.75													Minor Entrainment	
	180.12	3.0184	106.72	135.07	28.35													Minor Entrainment	
	190.09	3.1008	112.84	141.48	28.64													Entrainment	
	200.11	3.1814	118.25	148.62	30.37													Entrainment	
	210.12	3.2600	124.65	155.63	30.98													Entrainment	

**Two Layer**

**6mm Particles**

Shape: Spherical		Size: 6mm		Mass: 300g		Inclination: 10deg		Overlap: 18deg											
Data No.	$\Delta P$ across orifice mm $H_2O$	Reference Velocity m/s	$\Delta P$ across distributor mm $H_2O$	$\Delta P$ across distributor with particle mm $H_2O$	$\Delta P$ across bed mm $H_2O$	Slugging Width						Slugging Period					Observation		
						$W_1$ Ø	$W_2$ Ø	$W_3$ Ø	$W_4$ Ø	$W_5$ Ø	Avg Ø	$T_1$ sec	$T_2$ sec	$T_3$ sec	$T_4$ sec	$T_5$ sec		Avg sec	
		0			0														
	9.97	0.7101	7.51	12.15	4.64													Packed	
	20.02	1.0063	13.72	20.86	7.14													Packed	
	24.97	1.1238	16.86	22.05	5.19													Incipient	
	28.31	1.1966	18.73	23.82	5.09													Start Slugging	
	34.93	1.3292	22.66	27.76	5.1													Slugging	
	39.97	1.4219	25.53	30.89	5.36													Slugging	
	45.06	1.5097	28.73	34.23	5.5													Stop Slugging	
	50.07	1.5914	31.72	37.62	5.9													Swirling	
	59.95	1.7413	37.54	43.57	6.03													Swirling	
	70.05	1.8823	43.32	50.04	6.72													Fully Swirling	
	79.88	2.0101	49.29	55.96	6.67													Fully Swirling	
	90.09	2.1347	54.72	62.59	7.87													Entrainment	

**Extremely Shallow Bed**

Shape: Spherical		Size: 6mm		Mass: 400g		Inclination: 10deg		Overlap: 18deg											
Data No.	$\Delta P$ across orifice	Reference Velocity	$\Delta P$ across distributor	$\Delta P$ across distributor with particle	$\Delta P$ across bed	Slugging Width					Slugging Period					Observation			
	mm $H_2O$	m/s	mm $H_2O$	mm $H_2O$	mm $H_2O$	$W_1$	$W_2$	$W_3$	$W_4$	$W_5$	Avg	$T_1$	$T_2$	$T_3$	$T_4$		$T_5$	Avg	
						0	0	0	0	0	0	0	0	0	0	0	0	0	0
10.03		0.7123	7.51	11.31	3.8														Packed
20.04		1.0068	13.72	20.71	6.99														Packed
29.96		1.2310	19.58	27.93	8.35														Incipient
33.12		1.2943	21.64	29.72	8.08														Start Slugging
39.99		1.4222	25.53	34.05	8.52														Slugging
45.07		1.5098	28.73	37.14	8.41														Slugging
49.94		1.5893	31.72	40.25	8.53														Slugging
57.58		1.7066	36.26	45.04	8.78														Stop Slugging
70.02		1.8819	43.32	53.68	10.36														Fully Swirling
79.92		2.0106	49.29	59.06	9.77														Fully Swirling
90.01		2.1337	54.72	65.19	10.47														Fully Swirling
100.09		2.2500	61.02	71.37	10.35														Fully Swirling
109.96		2.3583	66.36	77.49	11.13														Fully Swirling
119.88		2.4624	72.84	83.43	10.59														Fully Swirling
130.11		2.5653	78.14	89.54	11.4														Fully Swirling
139.98		2.6609	83.24	96.18	12.94														Entrainment

**Extremely Shallow Bed**

Shape: Spherical		Size: 6mm		Mass: 500g		Inclination: 10deg		Overlap: 18deg											
Data No.	$\Delta P$ across orifice	Reference Velocity	$\Delta P$ across distributor	$\Delta P$ across distributor with particle	$\Delta P$ across bed	Slugging Width					Slugging Period					Observation			
	mm $H_2O$	m/s	mm $H_2O$	mm $H_2O$	mm $H_2O$	$W_1$	$W_2$	$W_3$	$W_4$	$W_5$	Avg	$T_1$	$T_2$	$T_3$	$T_4$		$T_5$	Avg	
						0	0	0	0	0	0	0	0	0	0	0	0	0	0
10.02		0.7119	7.51	11.75	4.24														Packed
19.98		1.0053	13.72	21.39	7.67														Packed
29.92		1.2302	19.58	30.48	10.9														Packed
34.91		1.3288	22.66	33.06	10.4														Incipient
37.57		1.3785	24.19	34.72	10.53														Start Slugging
45.03		1.5092	28.73	39.07	10.34														Slugging
49.94		1.5893	31.72	41.89	10.17														Slugging
60.05		1.7428	37.54	47.82	10.28														Slugging
69.21		1.8710	40.58	53.64	13.06														Stop Slugging
80.08		2.0126	49.29	60.05	10.76														Fully Swirling
89.91		2.1325	54.72	66.32	11.6														Fully Swirling
100.06		2.2497	61.02	72.54	11.52														Fully Swirling
109.94		2.3581	66.36	78.82	12.46														Fully Swirling
120.02		2.4639	72.84	85.26	12.42														Fully Swirling
130.16		2.5658	78.14	91.24	13.1														Fully Swirling
140.05		2.6615	83.24	97.62	14.38														Fully Swirling
150.15		2.7558	89.83	104.22	14.39														Fully Swirling
159.94		2.8443	95.66	110.58	14.92														Fully Swirling
170.08		2.9330	101.14	117.12	15.98														Fully Swirling
180.06		3.0179	106.72	123.56	16.84														Minor Entrainment
190.03		3.1003	112.84	129.84	17														Entrainment

**Extremely Shallow Bed**

Shape: Spherical		Size: 6mm		Mass:600g		Inclination: 10deg		Overlap: 18deg													
Data No.	$\Delta P$ across orifice mm $H_2O$	Reference Velocity m/s	$\Delta P$ across distributor mm $H_2O$	$\Delta P$ across distributor with particle mm $H_2O$	$\Delta P$ across bed mm $H_2O$	Slugging Width						Slugging Period					Observation				
						$W_1$ Ø	$W_2$ Ø	$W_3$ Ø	$W_4$ Ø	$W_5$ Ø	AVG Ø	$T_1$ sec	$T_2$ sec	$T_3$ sec	$T_4$ sec	$T_5$ sec		AVG sec			
			0																		
	9.98	0.7105	7.51		12.38																Packed
	20.04	1.0068	13.72		22.72																Packed
	29.97	1.2312	19.58		32.51																Packed
	35.09	1.3322	22.66		35.42																Incipient
	40.06	1.4235	25.53		38.29																Start Slugging
	49.96	1.5896	31.72		43.89																Slugging
	60.08	1.7432	37.54		49.71																Slugging
	70.05	1.8823	43.32		55.83																Slugging
	77.31	1.9775	47.74		60.34																Stop Slugging
	90.05	2.1342	54.72		68.41																Swirling
	99.97	2.2487	61.02		74.58																Fully Swirling
	110.13	2.3602	66.36		80.94																Fully Swirling
	120.06	2.4643	72.84		86.94																Fully Swirling
	130.02	2.5645	78.14		92.97																Fully Swirling
	140.05	2.6615	83.24		99.11																Fully Swirling
	149.92	2.7537	89.83		105.53																Fully Swirling
	160.06	2.8453	95.66		111.66																Fully Swirling
	169.96	2.9320	101.14		118.23																Fully Swirling
	180.05	3.0178	106.72		124.51																Fully Swirling
	189.92	3.0994	112.84		130.96																Fully Swirling
	200.09	3.1813	118.25		137.08																Fully Swirling
	210.08	3.2597	124.65		143.39																Minor Entrainment
	219.93	3.3353	130.72		149.88																Minor Entrainment
	229.89	3.4100	136.55		156.76																Entrainment
	240.08	3.4847	142.07		163.13																Entrainment

**Extremely Shallow Bed**

Shape: Spherical		Size: 6mm		Mass:700g		Inclination: 10deg		Overlap: 18deg														
Data No.	$\Delta P$ across orifice mm $H_2O$	Reference Velocity m/s	$\Delta P$ across distributor mm $H_2O$	$\Delta P$ across distributor with particle mm $H_2O$	$\Delta P$ across bed mm $H_2O$	Slugging Width						Slugging Period					Observation					
						$W_1$ Ø	$W_2$ Ø	$W_3$ Ø	$W_4$ Ø	$W_5$ Ø	AVG Ø	$T_1$ sec	$T_2$ sec	$T_3$ sec	$T_4$ sec	$T_5$ sec		AVG sec				
			0																			
	10.03	0.7123	7.51		12.84																	Packed
	20.02	1.0063	13.72		23.56																	Packed
	30.02	1.2322	19.58		33.59																	Packed
	40.06	1.4235	25.53		41.22																	Incipient
	44.93	1.5075	28.73		44.08		193	170	163	185	170	176.2	2.011	2.001	2.001	2.017	2.009	2.008				Start Slugging
	49.91	1.5889	31.72		46.96		204	178	200	193	206	196.2	2.281	2.268	2.286	2.256	2.309	2.28				Slugging
	60.02	1.7424	37.54		52.62		280	244	275	262	248	261.8	2.558	2.552	2.547	2.557	2.551	2.553				Slugging
	69.97	1.8812	43.32		58.65		297	305	290	307	292	298.2	3.128	3.148	3.164	3.134	3.121	3.139				Slugging
	82.74	2.0457	50.97		66.68																	Stop Slugging
	89.95	2.1330	54.72		70.96																	Swirling
	100.09	2.2500	61.02		77.65																	Fully Swirling
	110.04	2.3592	66.36		83.96																	Fully Swirling
	120.07	2.4644	72.84		89.89																	Fully Swirling
	130.09	2.5651	78.14		95.84																	Fully Swirling
	139.94	2.6605	83.24		101.68																	Fully Swirling
	150.07	2.7551	89.83		108.37																	Fully Swirling
	159.95	2.8443	95.66		114.62																	Fully Swirling
	169.89	2.9314	101.14		120.38																	Fully Swirling
	180.12	3.0184	106.72		126.85																	Fully Swirling
	190.04	3.1004	112.84		132.26																	Fully Swirling
	200.13	3.1816	118.25		138.38																	Fully Swirling
	210.04	3.2594	124.65		144.97																	Fully Swirling
	219.88	3.3349	130.72		151.95																	Fully Swirling
	230.09	3.4114	136.55		157.77																	Minor Entrainment
	239.93	3.4836	142.07		164.16																	Minor Entrainment
	250.13	3.5569	148.11		170.66																	Entrainment

Shape: Spherical		Size: 6mm		Mass:800g		Inclination: 10deg		Overlap: 18deg												
Data No.	$\Delta P$ across orifice mm $H_2O$	Reference	Velocity m/s	$\Delta P$ across distributor mm $H_2O$	$\Delta P$ across distributor with particle mm $H_2O$	$\Delta P$ across bed mm $H_2O$	Slugging Width					Slugging Period					Observation			
							$W_1$ °	$W_2$ °	$W_3$ °	$W_4$ °	$W_5$ °	Avg °	$T_1$ sec	$T_2$ sec	$T_3$ sec	$T_4$ sec		$T_5$ sec	Avg sec	
			0			0														
	9.99		0.7108	7.51	13.31	5.8													Packed	
	20.04		1.0068	13.72	24.35	10.63													Packed	
	29.94		1.2306	19.58	34.97	15.39													Packed	
	40.07		1.4236	25.53	43.61	18.08													Incipient	
	50.08		1.5916	31.72	49.38	17.66	173	166	161	178	161	167.8	1.953	1.944	1.925	1.927	1.937	1.937	Start Slugging	
	60.06		1.7429	37.54	55.19	17.65	248	229	223	228	220	229.6	2.287	2.311	2.307	2.301	2.304	2.302	Slugging	
	70.07		1.8826	43.32	61.31	17.95	252	306	265	295	295	282.6	2.752	2.728	2.744	2.727	2.747	2.74	Slugging	
	80.01		2.0117	49.29	67.63	18.34	334	337	310	340	335	331.2	2.737	3.665	3.694	3.615	3.678	3.478	Slugging	
	88.04		2.1102	54.13	72.92	18.79														Stop Swirling
	99.97		2.2487	61.02	80.41	19.39														Swirling
	110.04		2.3592	66.36	86.17	19.81														Swirling
	120.03		2.4640	72.84	92.66	19.82														Fully Swirling
	129.96		2.5639	78.14	98.84	20.7														Fully Swirling
	140.06		2.6616	83.24	104.94	21.7														Fully Swirling
	149.89		2.7534	89.83	110.85	21.02														Fully Swirling
	160.12		2.8459	95.66	117.38	21.72														Fully Swirling
	170.03		2.9326	101.14	123.57	22.43														Fully Swirling
	179.95		3.0169	106.72	129.85	23.13														Fully Swirling
	190.14		3.1012	112.84	136.07	23.23														Fully Swirling
	200.13		3.1816	118.25	142.38	24.13														Fully Swirling
	210.11		3.2600	124.65	148.62	23.97														Fully Swirling
	220.13		3.3368	130.72	154.93	24.21														Fully Swirling
	230.09		3.4114	136.55	161.54	24.99														Fully Swirling
	240.14		3.4852	142.07	167.71	25.64														Minor Entrainment
	250.12		3.5568	148.11	173.74	25.63														Entrainment

Shape: Spherical		Size: 6mm		Mass:900g		Inclination: 10deg		Overlap: 18deg													
Data No.	$\Delta P$ across orifice mm $H_2O$	Reference	Velocity m/s	$\Delta P$ across distributor mm $H_2O$	$\Delta P$ across distributor with particle mm $H_2O$	$\Delta P$ across bed mm $H_2O$	Slugging Width					Slugging Period					Observation				
							$W_1$ °	$W_2$ °	$W_3$ °	$W_4$ °	$W_5$ °	Avg °	$T_1$ sec	$T_2$ sec	$T_3$ sec	$T_4$ sec		$T_5$ sec	Avg sec		
			0			0															
	10.02		0.7119	7.51	15.04	7.53															Packed
	20.05		1.0070	13.72	27.46	13.74															Packed
	29.98		1.2314	19.58	39.14	19.56															Packed
	40.05		1.4233	25.53	45.13	19.6															Incipient
	50.06		1.5912	31.72	50.82	19.1															Incipient
	52.48		1.6292	33.37	52.25	18.88	185	193	184	169	171	180.4	1.852	1.834	1.822	1.817	1.842	1.833		Start Slugging	
	60.02		1.7424	37.54	56.53	18.99	230	218	230	220	227	225	2.054	2.059	2.046	2.042	2.047	2.05		Slugging	
	70.02		1.8819	43.32	62.48	19.16	280	256	265	258	267	265.2	2.344	2.326	2.351	2.327	2.344	2.338		Slugging	
	80.08		2.0126	49.29	69.03	19.74	298	310	310	310	323	310.2	2.765	2.761	2.762	2.769	2.759	2.763		Slugging	
	85.08		2.0745	52.62	72.06	19.44	334	330	322	332	327	329	3.061	3.043	3.037	3.047	3.018	3.041		Slugging	
	93.26		2.1719	57.21	77.62	20.41															Stop Slugging
	100.08		2.2499	61.02	81.78	20.76															Swirling
	109.93		2.3580	66.36	88.07	21.71															Swirling
	119.86		2.4622	72.84	94.23	21.39															Swirling
	129.96		2.5639	78.14	100.26	22.12															Fully Swirling
	140.04		2.6614	83.24	106.46	23.22															Fully Swirling
	150.12		2.7556	89.83	112.82	22.99															Fully Swirling
	160.08		2.8455	95.66	118.74	23.08															Fully Swirling
	169.92		2.9316	101.14	125.14	24															Fully Swirling
	180.09		3.0181	106.72	131.78	25.06															Fully Swirling
	190.12		3.1010	112.84	137.51	24.67															Fully Swirling
	200.09		3.1813	118.25	144.09	25.84															Fully Swirling
	210.02		3.2593	124.65	149.95	25.3															Fully Swirling
	220.14		3.3369	130.72	156.75	26.03															Fully Swirling
	230.04		3.4111	136.55	162.85	26.3															Fully Swirling
	240.06		3.4846	142.07	169.51	27.44															Minor Entrainment
	250.13		3.5569	148.11	174.84	26.73															Minor Entrainment
	259.88		3.6256	154.08	181.53	27.45															Entrainment

Shape: Spherical		Size: 6mm		Mass:1000g		Inclination: 10deg		Overlap: 18deg													
Data No.	$\Delta P$ across orifice mm $H_2O$	Reference	Velocity m/s	$\Delta P$ across distributor mm $H_2O$	$\Delta P$ across distributor with particle mm $H_2O$	$\Delta P$ across bed mm $H_2O$	Slugging Width					Slugging Period					Observation				
							$W_1$ Ø	$W_2$ Ø	$W_3$ Ø	$W_4$ Ø	$W_5$ Ø	Avg Ø	$T_1$ sec	$T_2$ sec	$T_3$ sec	$T_4$ sec		$T_5$ sec	Avg sec		
			0			0															
	9.98		0.71	7.51	14.52	7.01															Packed
	20.03		1.01	13.72	26.54	12.82															Packed
	30.07		1.23	19.58	37.63	18.05															Packed
	39.96		1.42	25.53	48.37	22.84															Incipient
	50.11		1.59	31.72	53.55	21.83															Incipient
	60.06		1.74	37.54	59.08	21.54															Incipient
	65.12		1.81	40.58	61.98	21.4	167	183	182	188	173	178.6	1.934	1.905	1.928	1.945	1.923	1.927			Start Slugging
	80.07		2.01	49.29	70.75	21.46	279	286	287	284	288	284.8	2.398	2.393	2.417	2.394	2.391	2.399			Slugging
	85.12		2.07	52.62	74.37	21.75	305	303	287	278	282	291	2.691	2.697	2.711	2.665	2.667	2.686			Slugging
	90.06		2.13	54.72	77.45	22.73	332	340	337	316	338	332.6	3.028	3.023	3.025	3.031	3.019	3.025			Slugging
	96.03		2.20	58.96	80.73	21.77															Stop Slugging
	110.02		2.36	66.36	89.47	23.11															Swirling
	120.08		2.46	72.84	96.15	23.31															Swirling
	130.05		2.56	78.14	101.94	23.8															Swirling
	139.96		2.66	83.24	108.76	25.52															Fully Swirling
	150.09		2.76	89.83	114.85	25.02															Fully Swirling
	159.88		2.84	95.66	121.08	25.42															Fully Swirling
	169.91		2.93	101.14	126.78	25.64															Fully Swirling
	179.94		3.02	106.72	133.67	26.95															Fully Swirling
	190.05		3.10	112.84	140.16	27.32															Fully Swirling
	200.06		3.18	118.25	145.84	27.59															Fully Swirling
	209.94		3.26	124.65	152.06	27.41															Fully Swirling
	219.84		3.33	130.72	158.27	27.55															Fully Swirling
	229.86		3.41	136.55	165.58	29.03															Fully Swirling
	240.07		3.48	142.07	172.09	30.02															Fully Swirling
	250.13		3.56	148.11	178.22	30.11															Minor Entrainment
	259.92		3.63	154.08	184.53	30.45															Entrainment

Shape: Spherical		Size: 6mm		Mass:1100g		Inclination: 10deg		Overlap: 18deg													
Data No.	$\Delta P$ across orifice mm $H_2O$	Reference	Velocity m/s	$\Delta P$ across distributor mm $H_2O$	$\Delta P$ across distributor with particle mm $H_2O$	$\Delta P$ across bed mm $H_2O$	Slugging Width					Slugging Period					Observation				
							$W_1$ Ø	$W_2$ Ø	$W_3$ Ø	$W_4$ Ø	$W_5$ Ø	Avg Ø	$T_1$ sec	$T_2$ sec	$T_3$ sec	$T_4$ sec		$T_5$ sec	Avg sec		
			0			0															
	10.03		0.7123	7.51	15.82	8.31															Packed
	20.04		1.0068	13.72	28.82	15.1															Packed
	30.03		1.2324	19.58	41.04	21.46															Packed
	40.01		1.4226	25.53	49.56	24.03															Incipient
	50.03		1.5908	31.72	55.24	23.52															Two layer ( Bubbling + swirling)
	59.94		1.7412	37.54	60.81	23.27															Two layer ( Bubbling + swirling)
	69.98		1.8814	43.32	66.79	23.47															Little bubble, slugging
	79.96		2.0111	49.29	72.73	23.44															Bubble, slugging
	90.04		2.1341	54.72	78.81	24.09															Bubble, slugging, swirling
	99.89		2.2478	61.02	85.11	24.09															Bubbling + Swirling
	110.08		2.3596	66.36	91.24	24.88															Bubbling + Swirling
	120.07		2.4644	72.84	97.31	24.47															Bubbling + Swirling
	129.92		2.5635	78.14	103.39	25.25															Bubbling + Swirling
	140.04		2.6614	83.24	109.75	26.51															Swirling
	149.95		2.7540	89.83	116.17	26.34															Swirling
	160.07		2.8454	95.66	122.24	26.58															Swirling
	169.92		2.9316	101.14	127.93	26.79															Swirling
	180.07		3.0179	106.72	134.07	27.35															Swirling
	190.09		3.1008	112.84	140.04	27.2															Swirling
	200.04		3.1809	118.25	146.56	28.31															Minor Entrainment
	210.09		3.2598	124.65	152.83	28.18															Minor Entrainment
	220.13		3.3368	130.72	159.23	28.51															Entrainment
	230.11		3.4116	136.55	166.07	29.52															Entrainment

**Two Layer**

