Experimental Studies on the Effect of the Particle Shape and Distributor Blade Overlap Angle on the Bed Pressure Drop in a Swirling Fluidized Bed

by

Jeevaneswary A/P Marimuthu

Dissertation submitted in partial fulfillment of
the requirement for the
Bachelor of Engineering (Hons)
(Mechanical Engineering)

MAY 2011

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CERTIFICATION OF APPROVAL

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Approved by,

(Prof Dr. Vijay R. Raghavan)

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK
May 2011

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 acknowledgement, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

JEEVANESWARY A/P MARIMUTHU

ABSTRACT

Swirling Fluidized Bed (SFB) is a newer variant of fluidized bed. Although it's been investigated by many researchers, a good understanding of its hydrodynamics and the effects of different design parameters on it is yet to be established. In fluidized bed processes, bed pressure drop is crucial as it determines the power required. The present work is an effort to investigate the effect of particle shape and distributor blade overlap angle on bed pressure drop in a SFB. In this study, bed particles of different shapes (cylindrical, spherical and oval) were used with different bed weights (500g, 750g and 1000g). The experiments were conducted with various distributor blade overlap angles (9°, 12°, 15° and 18°) at constant blade inclination of 10°. The experimental set up used in this research is shown in Figure 12 and Figure 18. Batch experiments were carried out with increasing the bed weight from 500g to 1000g in a step of 250g of bed particle for each shape and each distributor blade overlap angle. The results obtained were tabulated. Graphs were plotted to show the bed pressure drop variation with superficial velocity for each particle shape and distributor overlap angle. Figure 22 until Figure 39 show the results of this experiment. Result analysis confirmed that spherical particle has a higher bed pressure drop among the three shapes. Besides that, distributor blade overlap angle of 9° gives higher bed pressure drop as well. Hence, particle with spherical shape and blade overlap angle of 9° influenced the bed pressure drop the most. In the meantime, oval shape particles have lowest minimum fluidization velocity as compared to cylindrical and spherical particle. As a conclusion, the research conducted proves the superiority of SFB over conventional bed.

ACKNOWLEDGEMENT

A house is not built from a single brick. It's made up of many bricks joint together. Similarly, this research would not be completed successfully if there is no guidance or support from many people. Therefore, here, the author would like to express her utmost appreciation and gratefulness for those was the back bone for this research completion.

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ABBREVIATION AND NOMENCLATURES

a_m	Mean area (m^2)
Ar	Archimedes number
υ	Velocity
θ	Blade angle
ϵ	Fractional void volume
ε_M	Porosity at minimum fluidization
k	Fraction of the bed weight supported by fluidizing gas
ω	Angular velocity (rad s^{-1})
d_p	Particle diameter
ρ_p	Particle density
ρ_G	Gas density
g	Gravitational constant
μ_G	Gas viscosity
Δp	Pressure drop
$(\Delta p)_{b,s}$	Bed pressure drop in swirl mode
Re_{mf}	Reynolds number
U_{mf}	Minimum fluidization velocity
C_d	Drag coefficient
C_1	Particle shape dependant
C_2	Species dependant
R	Ratio of distributor pressure drop to bed pressure drop
L	Height of bed
M_b	Mass of bed (kg)
G	Mass-flow rate of fluid
D_p	Effective diameter of particles
SFB	Swirling Fluidized Bed
PVC	Polyvinyl Chloride

CHAPTER 1
INTRODUCTION

1.1 Project Background

Fluidization is a process whereby a bed of solid particles is transformed into a state where it behaves like a fluid when a gas or liquid is passed through this bed of particles. When the gas or liquid flows through the gaps in between the solid particles, it will exert a drag force on the particles. As the flow increases, the drag force exerted on the particles is large enough to disturb the arrangement of the particles. Then, the upward or vertical motion velocity is raised progressively, which makes the drag force exerted on the particles sufficient to support the particles' entire weight. Hence, the solid particles are said to be fluidized and behave like a fluid. As a result, the particles said to be having many properties and characteristics of a liquid such as the ability to free-flow under gravity.

The advantages of fluidization which is solid-fluid contacting are rapid mixing of solids, high rates of heat transfer as well as mass transfer and finally the containment of well-mixed solid particles at a uniform temperature that resists sharp temperature fluctuations and allows exothermic reactions to be carried out in controlled temperature. Therefore, it is widely used in applications such as heat recovery, treatment of metal surfaces, heat exchangers, gasification, and combustion of solid fuels, waste treatment, endothermic and exothermic reactions.

Limitations in conventional fluidized bed have resulted in development of new beds such as circulating fluidized bed, centrifugal fluidized bed, vibro-fluidized bed, magneto-fluidized bed, tapered fluidized bed, spouted fluidized bed and swirling fluidized bed. Swirling Fluidized Bed (SFB) is still very new in fluidization field. The gaseous medium in SFB enters at an angle through the inclined opening of the distributor where the vertical component causes fluidization and the horizontal component caused swirling motion. These features distinguish SFB with conventional fluidized bed.

1.2 Problem Statement

In industrial processes, which involve gas-solid contact, bed pressure drop is crucial in determining the power required. The process can be either diffusion controlled or kinetically controlled. Diffusion controlled process normally dependent on the porosity of the bed material used. The best example of the diffusion controlled process would be the drying of wheat. Meanwhile, kinetically controlled process is dependent upon the velocity of the gas flow. Combustion process is one of the kinetically controlled processes. Besides that, pressure drop also occurs due to the rearrangement of particles during fluidization. Rearrangement of particles occurs when the particle being lifted and fluidized inside the bed. Therefore, experimental studies need to be done in order to indentify the parameters that influence the bed pressure drop in SFB.

Hence, this project is carried out to study the effect of particle shape and distributor blade overlap angle on the bed pressure drop. Bed pressure drop is one of the hydrodynamic characteristics of Swirling Fluidized Bed (SFB). Therefore, experimental studies on the effect of the particle shape and distributor blade overlap angle will describe about the bed behavior which will affect the hydrodynamic behavior of SFB. Bed pressure drop also will have effect on the various reactions taken place inside the SFB. Thus, by analyzing the influence of the particle shape and distributor overlap angle on the bed pressure drop, one is able to control the kinetics of the different reaction occurring inside the SFB and also able to produce quality fluidization process.

There are numerous research are carried out in SFB field by many researchers from various countries all around the world. However, only few had conducted research on bed pressure drop. Moreover, this experiment is conducted with different particle shapes as well as different distributor blade overlap angles. Besides that, the author studies the relation between these two parameters, particle shape and distributor blade overlap angle, with bed pressure drop. Once, the author has studied the effect of these two parameters, she is able to know and analyze the behavior of the bed. Therefore, this project can be a good platform to study about the bed pressure drop.

In a nut shell, the results of this experiment not only will show superiority of SFB over conventional bed but also will establish a relation between the aspects discussed and the bed pressure drop.

1.3 Objectives and Scope of Study

1.3.1 Objectives

This project is regarding the Swirling Fluidized Bed (SFB). The author will study about the fluidization process and the hydrodynamic behavior of the SFB particularly on the effect of the particle shape and distributor blade overlap angle on the bed pressure drop. Therefore, below are the objectives of this project:

a) to study the effect of the particle shape on the bed pressure drop
b) to study the effect of the distributor blade overlap angle on the bed pressure drop
c) to establish relation between particle shape and distributor blade overlap angle with bed pressure drop

1.3.2 Scope of Study

At the end of this research, the author able to have the followings:

a) Better understanding of hydrodynamics of SFB
b) A new classification for particles in SFB, like Geldart classification in conventional bed
c) Effectiveness of the slugging regime in SFB

CHAPTER 2
LITERATURE REVIEW

2.1 Fluidization

In various technological operations it often requires to bring a granular material into intimate contact with a fluid. The simplest way of doing it is trough fluidization process. Fluidization is the fundamental concept that used to develop different types of fluidization bed and currently used in industrial applications such as circulating fluidized bed, centrifugal fluidized bed, vibro-fluidized bed, magneto-fluidized bed, tapered fluidized bed, spouted fluidized bed, swirling fluidized bed and etc. Since the conventional fluidized bed have certain limitations, therefore it leads to the further development in fluidized bed and as a result these fluidized beds are developed. The common feature shared among these fluidization beds is the fundamental concept, which these beds are based on; although they are differ to each other in certain aspects.

Vaněček C.Sc. et al (1966) says on increasing rate of flow, the pressure drop across the bed will also be increasing until, at a certain rate of flow, the frictional drag on the particles will become equal to the effective weight of the bed and in this state the bed of particles attains properties similar to those of fluids; hence it is called a fluidized bed. He also mentioned that this condition and the velocity corresponding to it are termed incipient fluidization and incipient fluidizing velocity respectively. Meanwhile, according to Kunii and Levenspiel (1990), at a point where all the particles suspended by the upward-flowing gas or liquid, the frictional force between particle and fluid just counterbalances the weight of the particles, the vertical component of the compressive force between adjacent particles is appears, and the pressure drop through any section of the bed about equals the weight of fluid and particles in that section, thus the bed is said to be fluidized. In other words, fluidization is a phenomenon of imparting the properties of a fluid to a bed of particles by passing a fluid through it at a velocity which brings the fixed bed to its loosest possible state just before transformed it into a fluidized bed. (Gupta and Sathiamoorthy, 1999, pg 1).

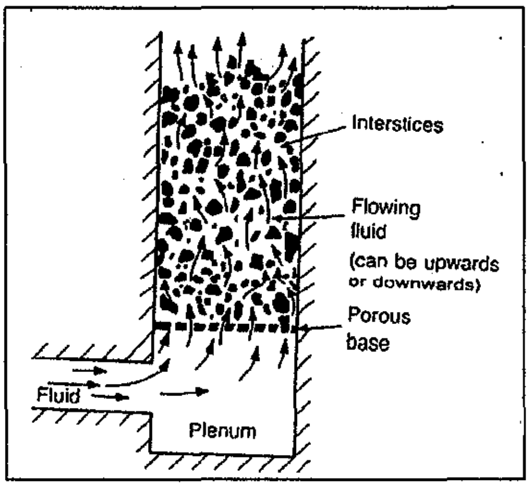


Figure 1: Schematic diagram of fluidization

Minimum fluidization velocity, U_{mf}, is important in fluidized bed. It is the velocity at which fluidization start to begin. According to K.S.Lim et al (1995), minimum fluidization velocity is based on the balance of pressure drops required to support the weight minus buoyancy acting on the particles at the point of minimum fluidization. Based on the Ergun's equation, minimum fluidization velocity, U_{mf}, is calculated using the equation below:

$$Re_{mf} = \sqrt{C_1^2 + C_2 Ar} - C_1$$

$$Re_{mf} = (\rho_G \, d_p \, U_{mf}) / \mu_G$$

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

Where:

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

ρ_p – Particle density

ρ_G – Gas density

d_p – Particle diameter

μ_G – Gas viscosity

U_{mf} – Minimum fluidization velocity

C_1, C_2 – Particle shape dependant and species dependant

Ar – Archimedes number

Re_{mf} – Reynolds number

Besides the equation mentioned earlier, U_{mf}, also can be found using Ergun's equation directly by substituting superficial fluid velocity with U_{mf} and the pressure drop across the bed is equal to the effective weight per unit area of the particles at the point of incipient fluidization as per below:

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

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

Rang r. Pattipati and C.Y. Wen (1981) said that the minimum fluidization velocity is affected by temperature. It decreases with increasing temperature for small particles. They also mention that for small particles and at high temperature, the viscous forces are dominant. However, for larger particles, kinetic forces are dominant compared to viscous forces.

Particles inside the fluidized bed are called bed particles. A fixed bed is a layer of particles which rest on one another and do not move relative to one another or relative to the walls of the container as said by Vaněček C.Sc. et al (1966). On the other hand, moving bed is a layer of particles moving as a whole under the action of gravity. After reach fluidization state, the volume of the bed is somewhat larger than the volume of the fixed layer. Thus, the bed is said to be expanded. If we further increase the velocity of the fluid, the bed continues to expand and the height of the bed increases. However, the concentration of particles per unit volume of the bed decreases.

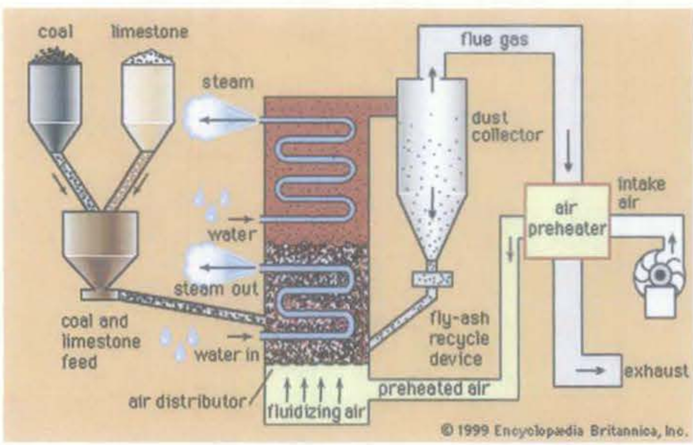


Figure 2: Conventional Fluidized Bed Combustor Boiler

The advantages and disadvantages of fluidized bed are illustrated in the table below based on Gupta et al (1999):

Table 1: Advantages and disadvantages of fluidization

Advantages	Disadvantages
• A high rate of heat and mass transfer under isothermal operating conditions is attainable due to good mixing.	• Fine-sized particles cannot be fluidized without adopting some special techniques, and high conversion of a gaseous reactant in a single-stage reactor is difficult.
• A fluid like behavior facilitates the circulation between two adjacent reactors.	• The hydrodynamic features of a fluidized bed are complex, and hence modeling and scale up are difficult.
• No moving part and it is not mechanically agitated reactor; hence low maintenance cost.	• Generation of fines due to turbulent mixing, gas or liquid jet interaction at the distributor site, and segregation due to agglomeration result in undesirable products.
• It is mounted vertically and save space.	• Elutriation of fines and power consumption due to pumping are inevitable.
• A continuous process coupled with high throughput is possible.	• Sticky materials or reactions involving intermediate products of a sticky nature would defluidize the bed.
• No skilled operator is required to operate the reactor.	• Highly skilled professionals in this area are needed for design and scale up.
• It is suitable for accomplishing heat-sensitive or exothermic or endothermic reaction.	• Limits on the operating velocity regime and on the choice of particle size range.
• It offers ease of control even for large-scale operation.	• Erosion of immersed surfaces such as heat-exchanger pipes may be severe.
• Multistage operations are possible hence the solids residence time as well as the fluid residence time can be adjusted to desired level.	• Reactions that require a temperature gradient inside the reactor cannot be accomplished in a fluidized bed reactor.

2.2 Swirling Fluidized Bed (SFB)

Swirling Fluidized Bed (SFB) is the latest development and the new variant in fluidized bed. Although SFB still a new variant, but the concept of SFB is commercially available in industrial applications. However, the published information on SFB behavior is insufficient. Therefore, there are plenty of opportunities in this field to be explored in order to improve the SFB. However, from the past research on SFB, it is known that SFB is more energy efficient compared to other methods of fluidization since in SFB each particle get equal opportunity to fluidize. Besides that, SFB has following advantages compared to conventional fluidized bed. (Vinod et al, 2010).

a) Low distributor pressure drop
b) No bubbling, hence absence of slugging and channeling
c) High quality fluidization with better mixing due to the toroidal motion of particles

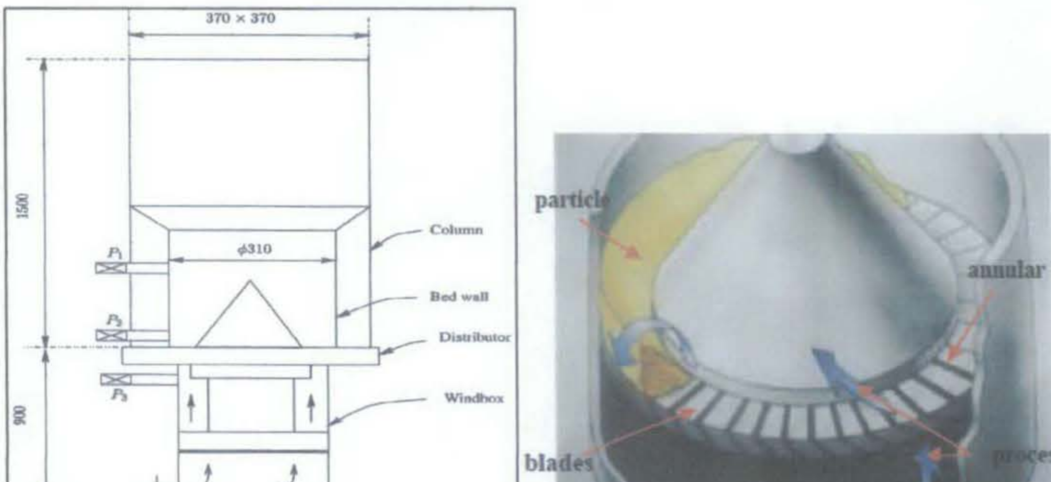


Figure 3: Schematic diagram and basic configuration of Swirling Fluidized Bed

Sreenivasan and Raghavan (2002), pioneers who were involved in developing SFB, said that gas enters the bed at an angle θ to the horizontal. Hence, velocity of the inclined injection of gas has two components; (i) a vertical component of, $\upsilon \sin \theta$, which causes fluidization, and (ii) a horizontal component, $\upsilon \cos \theta$, which is responsible for the swirl motion of the bed particle. As the gas penetrated deeper into the bed, its horizontal momentum is attenuated, and finally dies out at a certain height above the distributor, if the bed is sufficiently deep. If the bed is shallow enough, the velocity of the gas leaving the bed will still have two components.

Another author Paulose M.M (2006) mentioned in his thesis that SFB featuring an annular bed, where the inclined injection of gas trough the distributor. Therefore, the gas entering into the bed will have two components - horizontal and vertical components. (p.13). Thus, SFB has two significant advantages compared to other fluidized bed. This is because it can fluidize the particles at the same time causes swirling motion of particles on confined circular path.

Raghavan et al. (2004) stated that the swirling in the bed is a result of the transfer of angular momentum from the gas to the bed particles. However, this swirling motion is opposed by the frictional force introduced by the walls of the containing column. Observation in real bed shows that different region in the bed swirl with different velocities and thus the bed characteristics are functions of both radial and axial distance.

Furthermore, uniform distribution of fluid inside the SFB is very crucial in order to get uniform fluidization. SFB is capable of providing uniform fluidization which makes it useful in industrial applications such as drying, coating and etc. Therefore, distributors are very important components in a fluidized bed since it helps to distribute the air or gas uniformly inside the fluidized bed. It also associates with the pressure drop inside the fluidized bed.

In a conventional fluidized bed, air is admitted vertically upwards to the bed. On the other hand, in a swirling fluidized bed, air enters the bed at an angle and this is achieved by providing inclined holes or inclined slots in the distributor. It is a well accepted fact that high distributor pressure drop is required for good fluidization in conventional beds. On the other hand, quality fluidization can be achieved in a SFB with a comparatively lower distributor pressure drop. (Paulose M.M, 2006).

Kaewklum et al. (2010), cited that the fluid velocity is represented by its axial, radial and tangential components responsible for gas-solid transportation (mixing) in respective directions. He proved it based on his experimental studies on swirling fluidized bed combustor using an annular spiral air distributor.

The swirl motion in SFB is caused by the annular spiral distributors whereby there are number of blades arranged in spiral motion. The openings between the blades allow the air to flow from the plenum chamber into bed. The inclined motion of the air causes the swirl of the particles inside the SFB. The concept of annular spiral distributor is inspired from Ouyang and Levenspiel (1986) work where in they proposed a spiral distributor for swirl motion. They found out from their experiment that pressure drop across the spiral distributor is from 1 to 2 orders of magnitude smaller than for the sintered plate tested; however, this pressure drop increases more rapidly with an increase in gas velocity than for the sintered plate. Vinod et al. (2010) in his paper "Study of the Fluid Dynamic Performance of Distributor Type in Torbed Type Reactors" said that the percentage useful area of the distributor was about 95 in the inclined blade type distributors, while it was 64 in the perforated plate type distributor.

Sreenivasan (1995) has conducted experiments in a SFB with a distributor capable of giving swirl motion to the bed particles. In this experiment, the distributor was made of a number of blades that are truncated sectors of a circle with each blade inclined at an angle of 12^{o} to the horizontal. Since hollow metallic cone was placed at the centre of the bed to avoid particle accumulation, the area at the centre of the distributor which was covered by the cone was not utilised. Hence the static bed height will be more for a given weight of the material than in a conventional fluidized bed.

Certain drawbacks in conventional fluidized bed which lead to development of SFB and other fluidization beds are limitation in gas flow rate to avoid elutriation in gas-fluidized beds, and limitations on particles size, size distribution and particle shapes. However, SFB provides an efficient contact between gas and particles compared to conventional fluidized bed. Conventional bed requires high pressure drop for fluidization as compared to SFB where it emphasize on quality fluidization. Besides that, due to the cross flow of the particles, no stable jet formation occurs in the SFB. The toroidal motion in the bed mixes the particles in the radial direction. The gas velocity can be increased to high values with little elutriation. In addition, SFB have distinct advantages in drying of agriculture produce. (Paulose M.M, 2006, pg 2). These are the advantages of SFB over conventional fluidized bed.

The table below illustrates the comparison between conventional fluidized bed and SFB:

Table 2: Comparison between conventional fluidization bed and SFB

Conventional Fluidized Bed	**Aspect**	**Swirling Fluidized Bed (SFB)**
• Fluid enters into the bed in direction only, which is vertical motion	Direction of fluid flow	• Fluid enter into the bed in two direction – vertical and horizontal motion
• Only have fluidization	Process	• Have both swirling and fluidization at the same time
• Perforated or porous plate distributors	Types of distributor	• Annular spiral distributor
• Good fluidization require high distributor pressure drop	Type of fluidization	• Quality fluidization is achieved with a comparatively lower distributor pressure drop
• Limitations such as slugging, channeling, elutriation of solid particles, limitation in size of particles	Limitations	• Limitation due to the use of annular area of the distributor, which causes restriction in its size

Therefore, SFB has more advantages and applications compared to conventional fluidized bed. Since it has wider characteristics and applications, it is very much used in the industries.

2.3 Distributor Pressure Drop

Distributors are a series of blades that has been arranged in spiral motion. These distributors' blades are arranged in an inclined angle to allow gas or air to pass trough. As the name applies, it is used to distribute the air or gas uniformly inside the SFB. Therefore, it is one of the crucial components in the fluidized bed and it also influences the process undergoing inside the bed.

Type of distributor used in this experiment is annular spiral distributor, where the blades are arranged in the clockwise direction and hence the air flow is also in clockwise direction. The figure below shows the example of an annular spiral distributor; where the flow is in counter clockwise direction and the annular spiral distributor used in this experiment respectively.

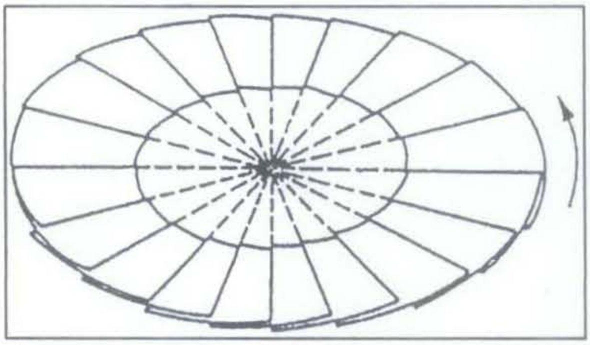



Figure 4: Annular spiral distributor

Paulose M.M (2006) says that a good gas distributor shall possess the following qualities:

1. Have low distributor pressure drop at the operating velocity so as to minimize the power consumption.
2. Be strong enough to withstand both thermal and mechanical stresses.
3. Ability to prevent particle flow back to the plenum chamber at low airflow.
4. Have minimum particle attrition.
5. Ability to prevent distributor attrition.

Distributor pressure drop is very important since it will determine the air flow inside the fluidized 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. Therefore, distributor design is very important.

Paulose M.M (2006) says that ratio of the distributor pressure drop to the bed pressure drop (R) is generally considered for the design of distributors in conventional bed. Hiby (1967) mentioned that the minimum ratio of distributor to bed pressure drop, depends not only on the distributor type but also on the fluidized particles, the bed depth, the superficial gas velocity, bed aspect ratio and even the percentage of uneven distribution which can be tolerated. Few researchers have come out with values for R according to material used and different types of plates used.

Meanwhile, Sathyamurthy et al. (1977) observed that the number of orifices or percentage open area is determined by the gas flow rate, bed height, bed material and type of distributor. He also observed that a higher bed pressure drop is required to operate all orifices in case of finer size particles. Whitehead (1971) stated that it is dangerous to postulate universal rules for distributor pressure drop in terms of a fixed value for the ratio and to attempt to apply them to all situations.

Thus, distributors are one of the important components in SFB since its pressure drop very crucial in providing a uniform air flow inside the fluidized bed.

2.4 Bed Pressure Drop

In fluidized bed processes bed pressure drop is crucial as it determines the power required. Bed pressure drop is the pressure difference between total pressure drop and distributor pressure drop. Therefore, it is the pressure of the bed particle, which shows the behavior of the bed particles. Ergun (1986) has established that the pressure drop in a fluidized bed is due to the simultaneous kinetic and viscous energy losses. Therefore, he had done experimental and analytical studies and came out with an equation called Ergun's equation. The equation is:

$$\frac{\Delta P}{L} g_c = 150 \underbrace{\frac{(1-\epsilon)^2}{\epsilon^3} \frac{\mu U_m}{D_p^2}}_{\text{Viscous energy losses}} + 1.75 \underbrace{\frac{(1-\epsilon)}{\epsilon^3} \frac{G U_m^2}{D_p}}_{\text{Kinetic energy losses}}$$

Where:

ΔP	- Pressure loss	G	- Mass-flow rate of fluid
D_p	- Effective diameter of particles	L	- Height of bed
g_c	- Gravitational Constant	ϵ	- Fractional void volume
μ	- Absolute viscosity of fluid		
U_m	- Superficial fluid velocity assured at average pressure		

Above equation has been examined from the point of view of its dependence upon flow rate, properties of the fluids, and fractional void volume, orientation, size, shape and surface of the granular solids. However, Ergun considered the following factors in his equation.

a) Rate of fluid flow
b) Viscosity and density of the fluid
c) Closeness and orientation of packing
d) Size, shape and surface of the particles

Sreenivasan and Raghavan (2002) said a striking feature that distinguishes the swirling bed from a conventional fluidized bed is that, the bed pressure drop in the swirling mode, $(\Delta p)_{b,s}$ increases with air velocity. This is because the bed pressure is proportional to the centrifugal weight of the bed. They conducted experiment in swirling bed for two different size of spherical PVC particle. The founding of the experiment is that the pressure drop in the swirling regime is not constant, but increases with gas flow rate and also proposed that the pressure drop increases with centrifugal weight of the bed or the angular velocity of particle. During their experiment, they came across the following regimes in their bed:

a) Bubbling
b) Wave motion with dune formation
c) Two-layer fluidization
d) Stable swirling

Both researchers model the pressure drop, $(\Delta p)_{b,s}$, in the swirling regime of operation. Their principle assumptions are:

a) The bed is a single swirling mass of uniform angular velocity
b) The angular velocity of the gas at the free surface of the bed is approximately equal to the mean angular velocity of the bed

Figure below shows the result of the experiment carried out by Sreenivasan and Raghavan. Their experiment predicts the pressure drop in the packed regime using Ergun equation to within 20% of the experimental values.

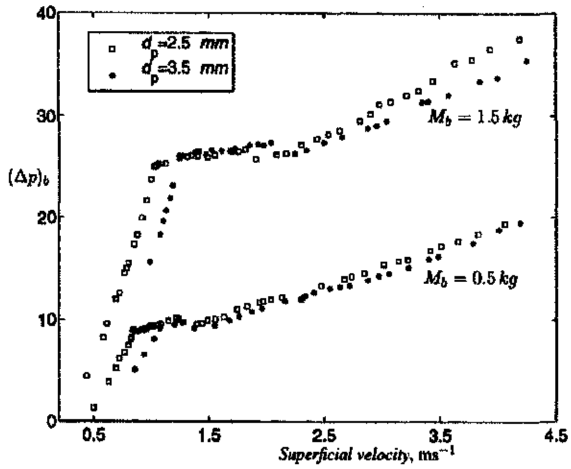


Figure 5: Experimentally obtained bed pressure drop, in mm of water

From their experiment, the pressure drop of fluidization may be expressed as:

$$(\Delta p)_{fl} = kM_b/a_m.$$

Meanwhile, the pressure drop in the swirling region can be predicted using the following equation:

$$(\Delta p)_{b,\,s} = (\Delta p)_{fl} + \psi\omega^2$$

In another research, Mohd Faizal et al (2010) found that the pressure drop of the bed increased with superficial velocity after minimum fluidization, in contrast with a conventional fluidized bed. They also found that the blade geometry has less effect on bed performance, compared to fraction of open area and particle size. This experiment was carried out to know the influence of the superficial velocity, bed weight, blade overlapping angle and number of blades on the bed pressure drop. The results of the research are shown in the figures followed.

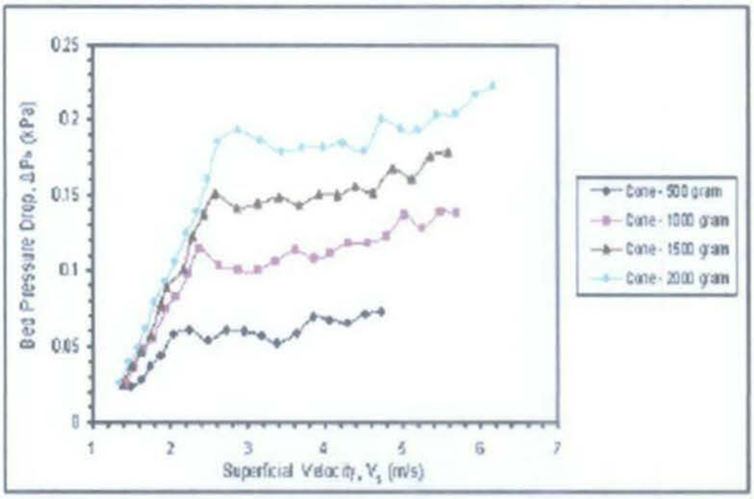


Figure 6: Bed pressure drop against superficial velocity for variable bed loading

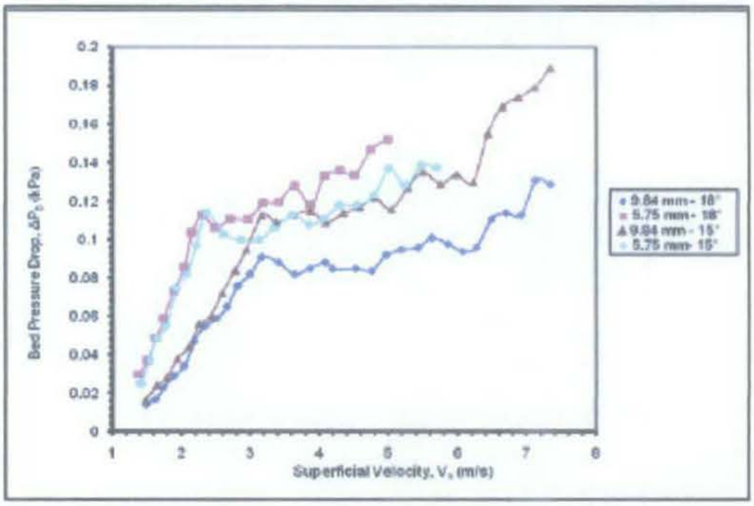


Figure 7: Bed pressure drop against superficial velocity for different blade overlapping angle

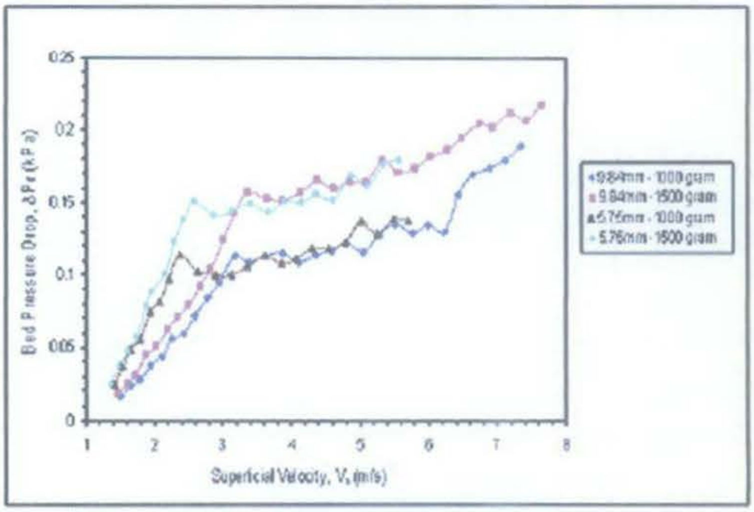


Figure 8: Bed pressure drop against superficial velocity for different bed weight

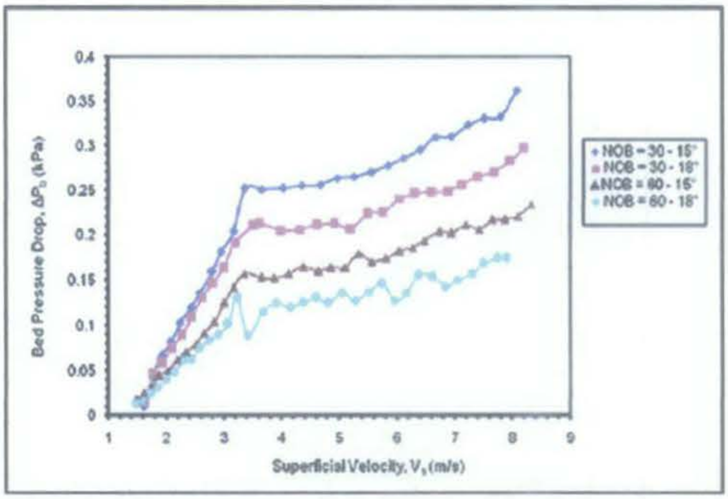


Figure 9: Bed pressure drop against superficial velocity for different number of blades

K.V.Vinod et al (2010) studied about the bed pressure drop as a function of superficial velocity by using three types of distributor, which are inclined blades in a single row, perforated plate with inclined holes and inclined blades on three rows. Their experiment finding reveals that for each bed weight studied, the bed pressure drop was almost constant after minimum fluidizing velocity of about 1.2m/s. The results of the experiment are shown in the Figure 10.

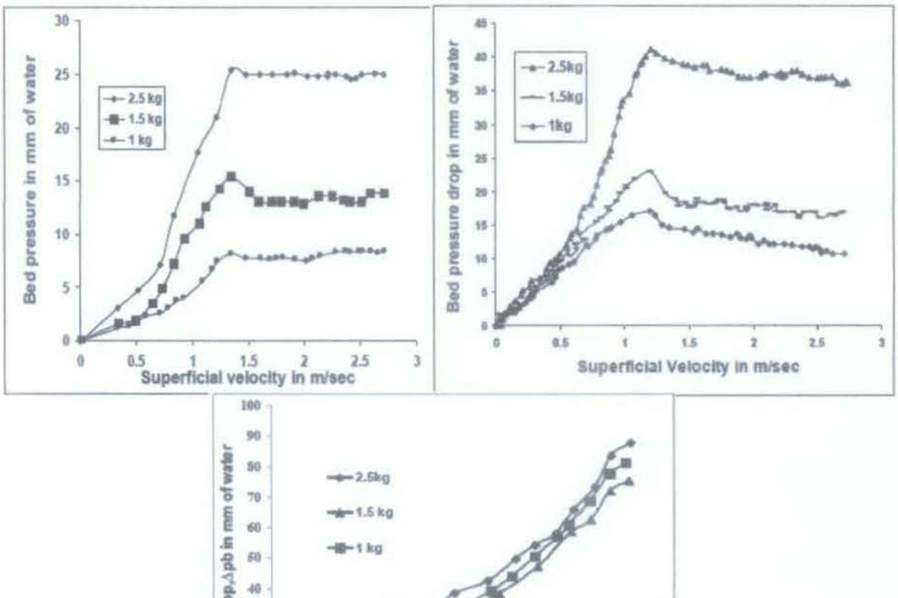


Figure 10: Variation of bed pressure drop with superficial velocity for the inclined-blade three-row, inclined-blade single-row and perforated plate with inclined hole type distributor respectively

Raghavan and Vinod (2011) in their research on operation of a swirling fluidized bed quoted that the bed pressure drop first show an upward trend and then reaching after a particular peak value it start decreasing. This may be attributed to the fact that the bed pressure drop will fall as the resistance from the bed decreases. Besides that, they said that the peak in the bed pressure drop can also be explained as being due to the additional energy required for rearrangement of the 'locked' particles.

In this research, the variation of bed pressure drop was shown against superficial velocity. In order to find the superficial velocity, author measures the pressure drop in orifice meter and used the following equations to calculate the flow rate in m^3/s and superficial velocity in m/s respectively.

$$\text{Flow rate} = \frac{C_d \times \sqrt{2 \times g \times \Delta p_{air}}}{\sqrt{1-(d/D)^4}} \times \text{Orifice Area}$$

$$V_{Superficial} = \frac{\text{Flow rate } (m^3/s)}{\text{Bed area } (m^2)}$$

In case of SFB, the bed pressure also occurs due to the rearrangement of particles during fluidization. When the gas enters the bed trough the distributor, the packed bed slowly gets fluidized and the bed expands. The particles get lifted up and swirl in the direction of the gas as illustrated in Figure 11. So some extra energy has to be spent to unlock the particles from the packed state in order to get them fluidized.

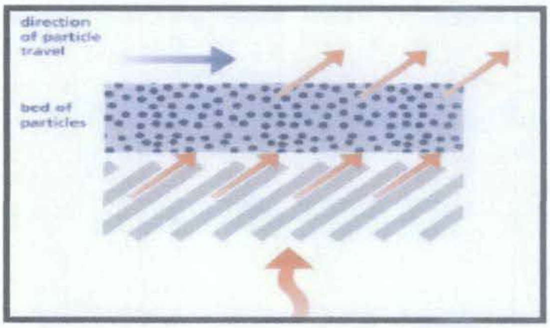


Figure 11: Rearrangement process

Only few researchers had done research on bed pressure drop. However, their research usually will be a part of another research. No one had dedicated a research solely on bed pressure drop. Therefore, the author gets an advantage since her research is fully on the bed pressure drop and the parameters that influence the bed pressure drop.

CHAPTER 3
METHODOLOGY

3.1 Experimental Set Up

The schematic diagram of the test set-up for this experiment is shown in the Figure 12. This test set-up consists of a Perspex cylinder, which forms the bed wall. The cylinder is mounted on the distributor. The type of distributor used in this test is flexible version of annular spiral distributor. It is a variant of the spiral distributor developed by Ouyang and Levenspiel (1986). Unlike in case of Ouyang and Levenspiel the blades are not welded at the centre for the sake of flexibility in changing the blades with different overlapping angle during the experiment. The trapezoidal shaped blades are made of 1mm Aluminium and there are sixty of them. The blades are arranged on stepped rings, an outer and inner, with steps machined at an angle of 10° to the horizontal. The blades are held intact by two other rings, an outer and inner, on the top. The inclined overlapping blades direct the fluidizing air as desired. A thin cylindrical shape metal of 5mm thick is screwed at the centre of the bed above the stepped rings in order to keep the blades in place tightly. The stepped rings and the blades are arranged around the Bakelite. The blades and annular spiral distributor used in this experiment is shown in the Figure 14 and Figure 16 respectively.

Both the Perspex cylinder and distributor are mounted on the plenum chamber by using bolts and nuts. The author did not prefer using permanent joint because it will be easier to use bolts and nuts whenever the author needs to change the distributor blades. The plenum chamber is a hollow cylinder with a hole at one of its side for the air entry. A flange is welded to the plenum chamber at the hole in order to connect the chamber to the pipes. The chamber is connected to the blower with PVC pipes. There are two paths for the air to flow, which are larger flow and lower flow. This flow is controlled by two butterfly valves. If the air flows from the blower through the first butterfly valve, the second butterfly valve will be closed and vice versa. Two orifice plates are mounted at middle of the pipe connecting the blower and plenum chamber to measure the air flow rate.

A hollow metal cone is centrally located at the base of the bed. This cone causes the superficial velocity of the air decreases continuously from the distributor to the free surface of the bed. Besides that, it also eliminates the 'dead zone' at the centre of the bed (Sreenivasan and Raghavan, 2002). Then, three pressure tappings, P_1, P_2 and P_3 are provided on the set up to measure the pressure drops using digital manometer. P_1, and P_2, are on the Perspex bed wall while P_3 is on the plenum chamber wall below the distributor plane. The complete and overall experimental set up is shown in the Figure 18.

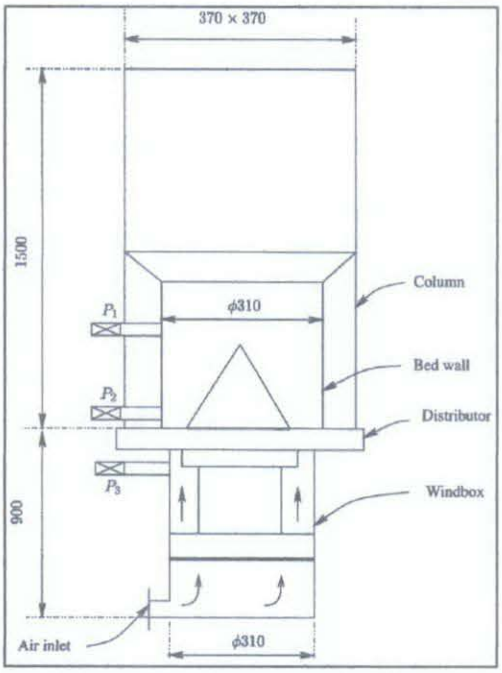


Figure 12: Experimental Test

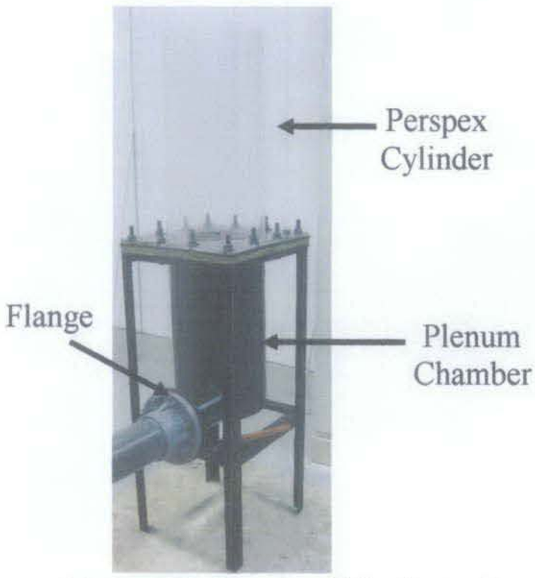


Figure 13: Perspex Cylinder and plenum chamber which make up the bed

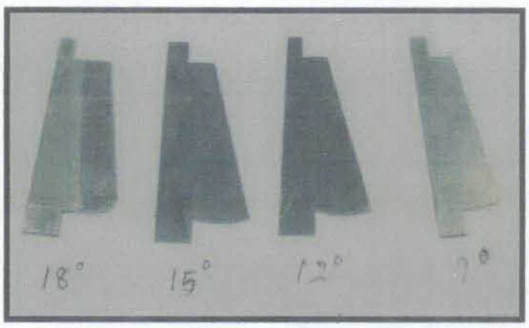


Figure 14: Shape of blade used in this experiment

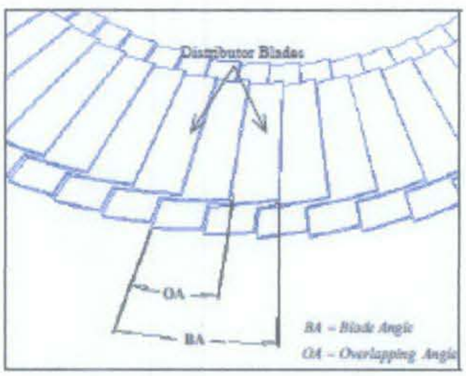


Figure 15: Blade overlap angle

Figure 16: Annular Spiral Distributor

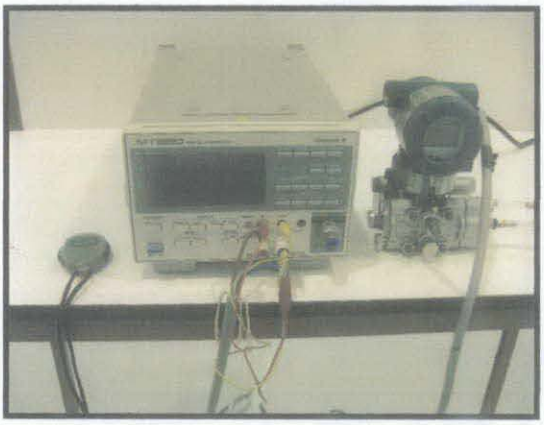


Figure 17: Digital Manometer

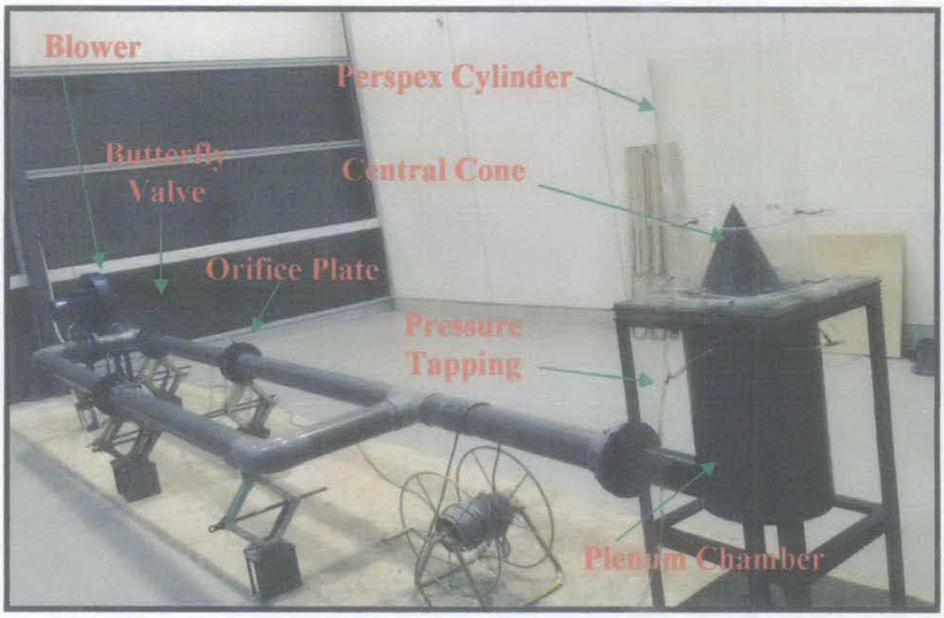
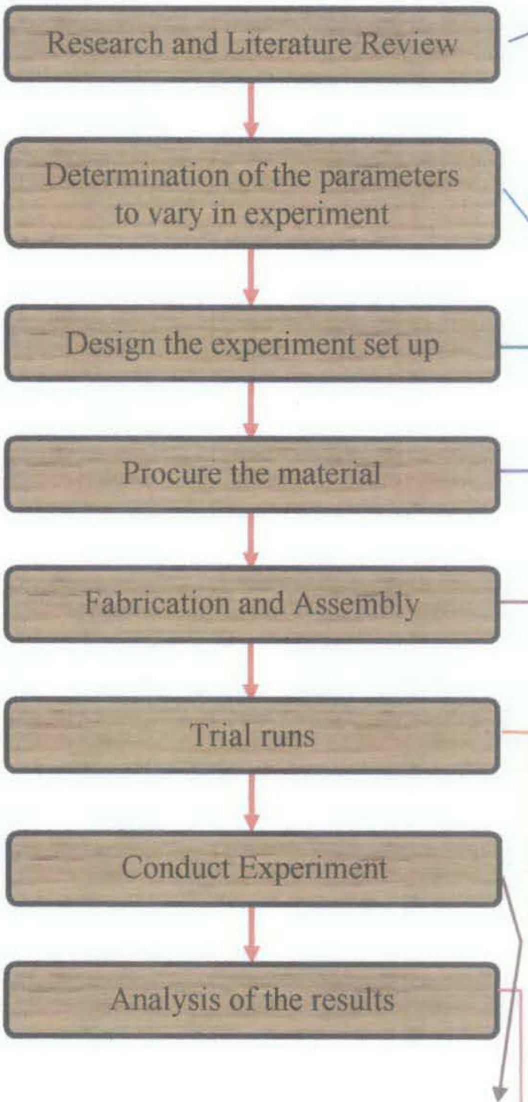


Figure 18: Overall Experimental Set up

3.2 Procedures of the Experiment

3.2.1 Flow chart



Research and literature review were conducted to have better understanding of SFB concept. Author read journals published about SFB to know about the development in SFB.

The effect of particle size and distributor blade overlap angle on bed pressure drop in SFB has not been explored so far. Thus, author chooses these two parameters in her experiment.

With the help of a PhD student, author design the experiment set up.

Author procure material needed for her experiment set up such as aluminium sheet, PVC pipes and etc and get endorsed by her supervisor.

Equipment parts such as plenum chamber were fabricated by fabricator and assembly of the set up was done by the author with the help of a PhD student.

Trial runs were conducted in order to test the experiment set up.

The experiment was conducted with three different particles with three different weights and four distributor blade overlapping angles. The detailed experiment procedures are explained in the following section.

The results were tabulated and analyzed using graphs. Detailed results description is shown in result section.

3.2.2 Procedures

1. Blades of overlap angle 9° are arranged on the inner stepped ring at Bakelite and the outer stepped ring is placed on the blades to keep the blades in place.
2. The thin cylindrical shape metal of 5mm thick is screwed at the centre of the bed above the stepped rings in order to keep the blades in place tightly.
3. Then, the central cone is screwed at the center of the bed.
4. Next, the Perspex cylinder is screwed with bolts and nuts to the plenum chamber.
5. The experiment set up is tested with the blower switched on to confirm the experiment set up works well without any failure or leakage.
6. Blower is switched on again.
7. Then, the distributor pressure drop, (P_2 - P_3) is measured at different air flow rates.
8. The air flow rate is varied progressively using a butterfly valve.
9. The air flow rate is measured using an orifice flow meter.
10. The bed is loaded with 500g cylindrical particle.
11. The total pressure drop, P_3, is measured for different air flow rate.
12. Then, the experiment is continued with 750g and 1000g of cylindrical particle.
13. The experiment is repeated for blade overlap angles of 12°, 15° and 18° with spherical and oval shape particles.

Basically, the experiment was conducted in batch with the following condition:

- Particle shape: Spherical (1mm), Cylindrical (L/D =3.5), Oval (2mm minima dia.)
- Particle weight (g): 500, 750, 1000
- Blade overlap angle: 9°, 12°, 15° & 18°

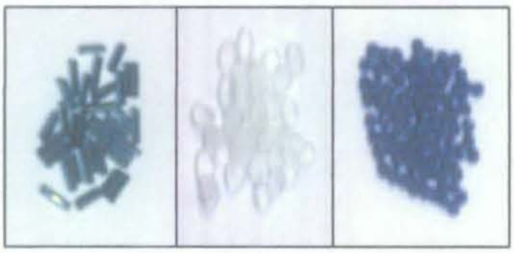


Figure 19: Cylindrical, Oval and Spherical particle respectively

All the readings were inserted in a Microsoft Excel sheet. Finally, the bed pressure drop is the pressure difference between the total pressure drop and distributor pressure drop i.e. (P_1 - P_3). Graphs were generated to analyze the effect of particle shape and blade overlap angle on bed pressure drop. It will be discussed in results section.

3.3 Project Planning (Gantt chart)

Milestone for Final Year Project I

No	Detail/Week	1	2	3	4	5	6		7	8	9	10	11	12	13	14
1	Selection of project topic	■						Mid Semester Break								
2	Confirmation of project topic		■													
3	Literature review studies		■	■	■											
4	Submission of preliminary report				●											
5	Fabrication & Experimental set up					■	■		■							
6	Trial tests									■	■					
7	Submission of progress report									●						
8	Seminar									●						
9	Initial Experiments on the setup											■	■	■	■	
11	Submission of interim report															●
12	Oral presentation								During Study Week							

● Suggested milestone

■ Process

Figure 20: Gantt chart of FYP I

Milestone for Final Year Project II

No	Detail/Week	1	2	3	4	5	6	7	Mid Semester Break	8	9	10	11	12	13	14
1	Cylindrical Shape experiment	■														
2	Spherical Shape experiment		■													
3	Oval Shape experiment			■												
4	Result Analysis				■	■	■	■		■						
5	Progress report Submission									●						
6	Repeat the experiment									■	■	■	■			
7	Result Analysis									■	■	■	■			
8	Poster exhibition												●			
9	Submission of dissertation (soft)														●	
10	Oral presentation															●
11	Submission of dissertation(hard)									7 Days after Oral Presentation						

● Suggested milestone

■ Process

Figure 21: Gantt chart of FYP II

CHAPTER 4
RESULTS AND DISCUSSIONS

4.1 Results

Although there are many feasible permutations of results are possible from the data acquired from the experiment, only a few are presented here.

4.1.1. Effect of Particle Shape on Bed Pressure Drop

4.1.1.1. Distributor Blade Overlap Angle of 9°

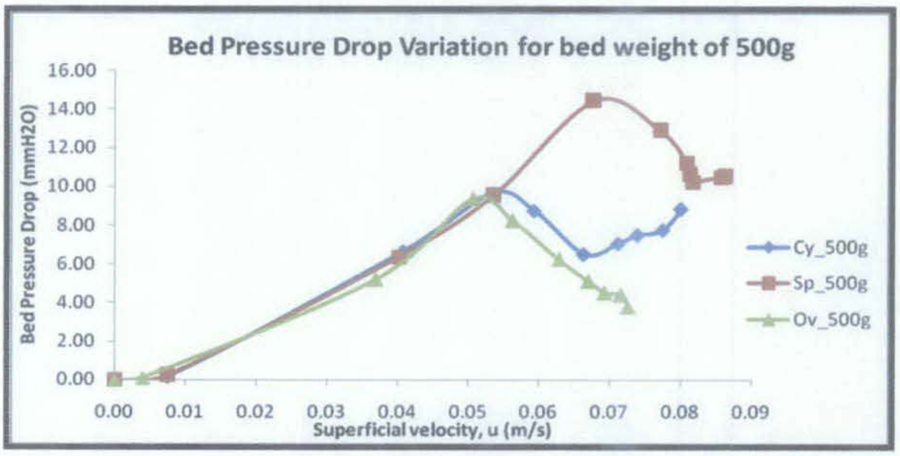


Figure 22: Variation of bed pressure drop with $V_{Superficial}$ with blade overlap angle of 9° for different shape of particle with bed weight of 500g

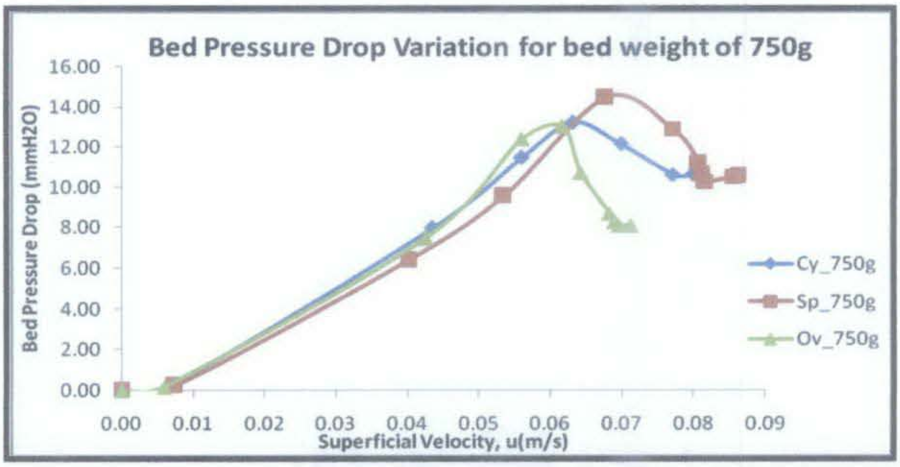


Figure 23: Variation of bed pressure drop with $V_{Superficial}$ with blade overlap angle of 9° for different shape of particle with bed weight of 750g

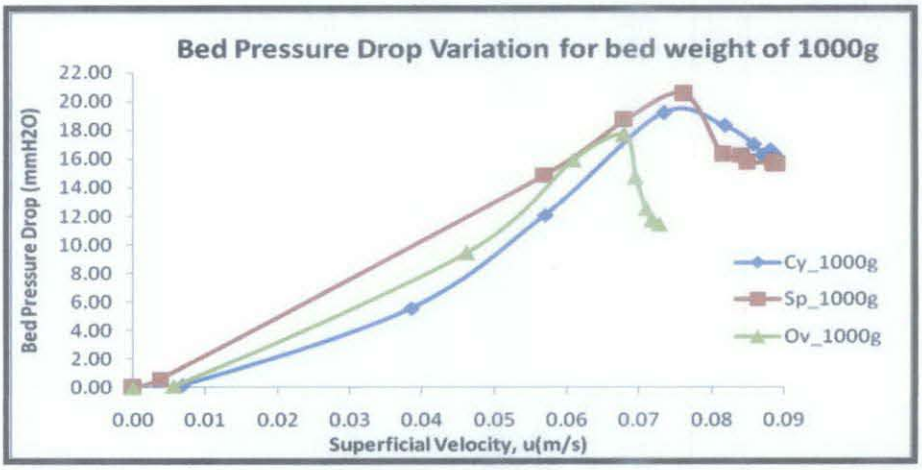


Figure 24: Variation of bed pressure drop with $V_{Superficial}$ with blade overlap angle of 9° for different shape of particle with bed weight of 1000g

4.1.1.2. 12° Distributor Blade Overlap Angle

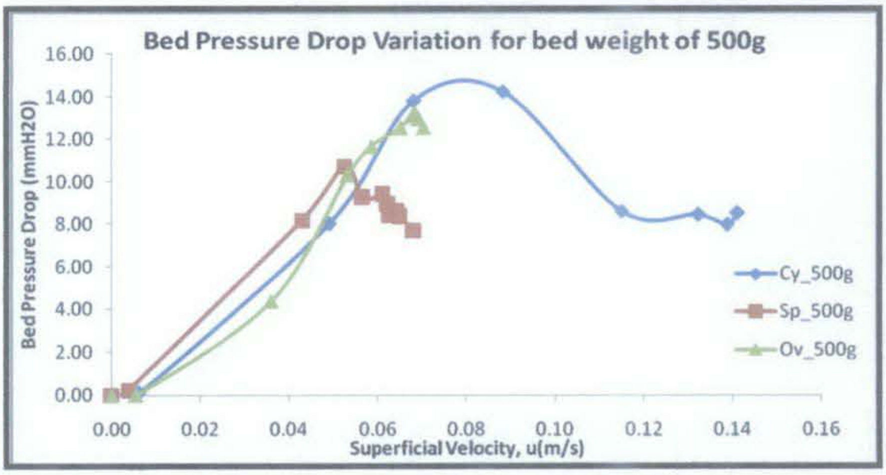


Figure 25: Variation of bed pressure drop with $V_{Superficial}$ with blade overlap angle of 12° for different shape of particle with bed weight of 500g

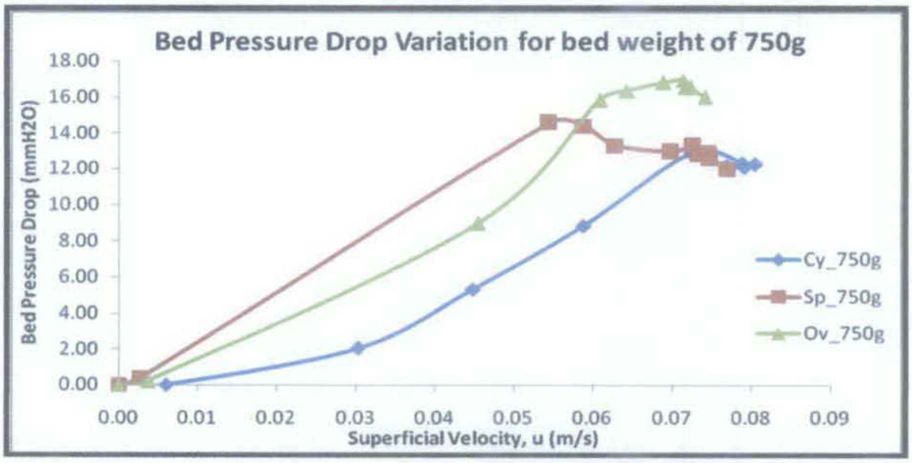


Figure 26: Variation of bed pressure drop with $V_{Superficial}$ with blade overlap angle of 12° for different shape of particle with bed weight of 750g

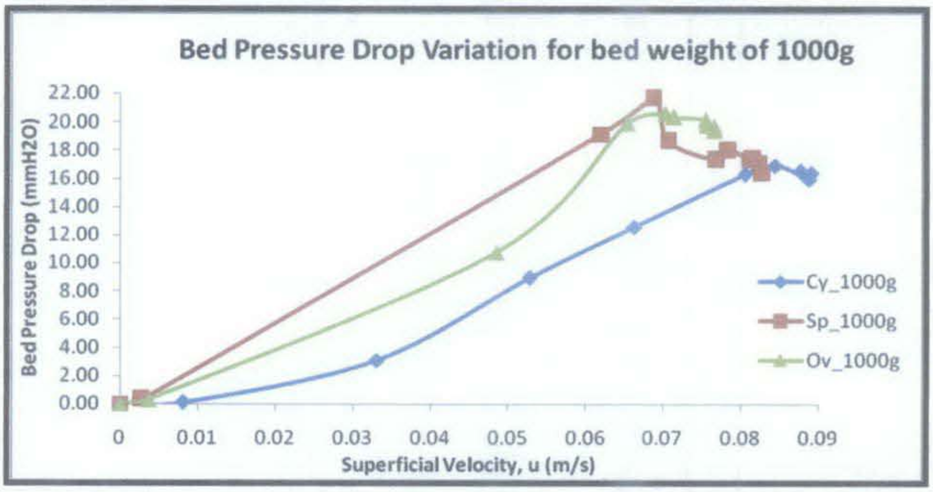


Figure 27: Variation of bed pressure drop with $V_{Superficial}$ with blade overlap angle of 12° for different shape of particle with bed weight of 1000g

4.1.1.3. 15° Distributor Blade Overlap Angle

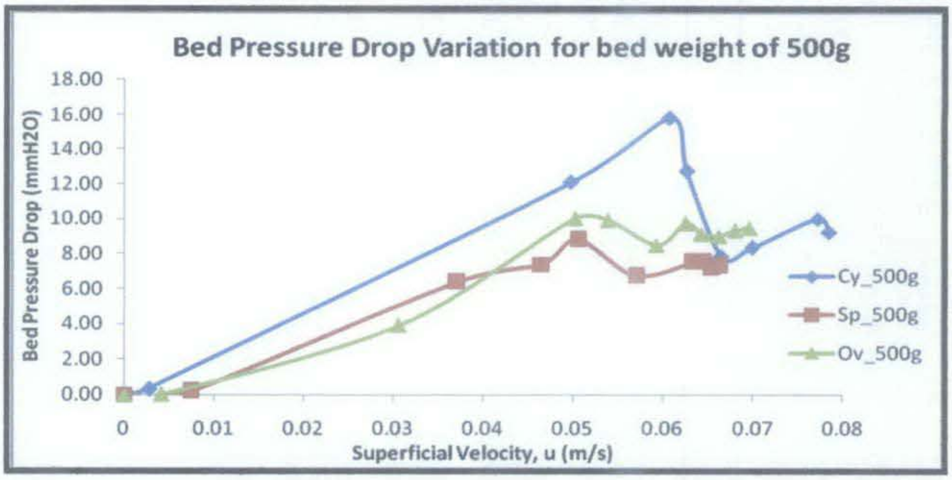


Figure 28: Variation of bed pressure drop with $V_{Superficial}$ with blade overlap angle of 12° for different shape of particle with bed weight of 500g

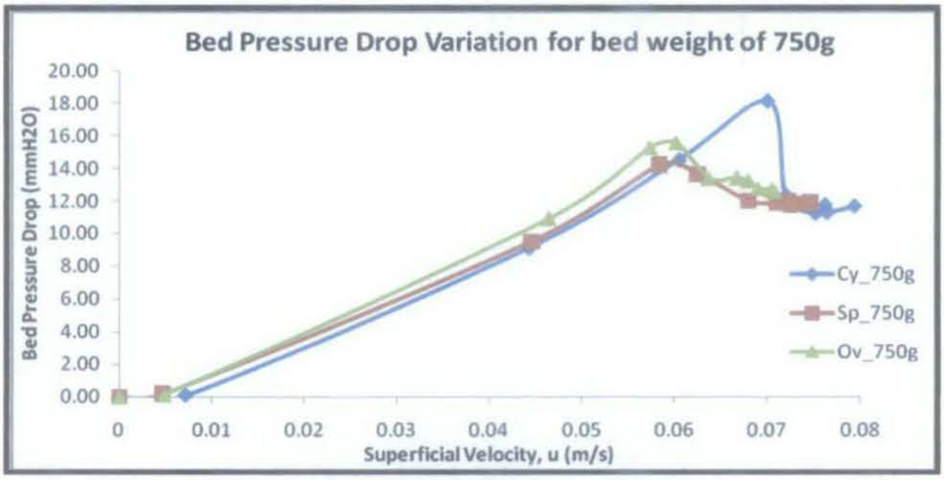


Figure 29: Variation of bed pressure drop with $V_{Superficial}$ with blade overlap angle of 15° for different shape of particle with bed weight of 750g

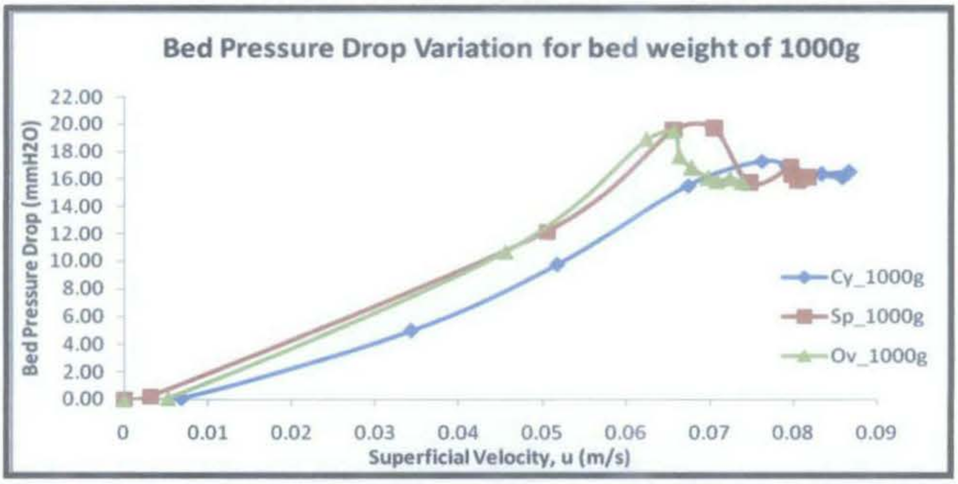


Figure 30: Variation of bed pressure drop with $V_{Superficial}$ with blade overlap angle of 15° for different shape of particle with bed weight of

4.1.1.4. 18° Distributor Blade Overlap Angle

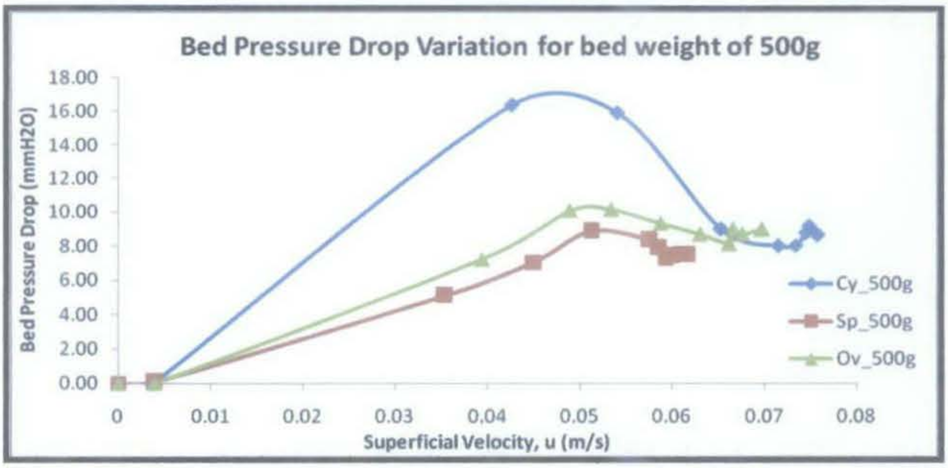


Figure 31: Variation of bed pressure drop with $V_{Superficial}$ with blade overlap angle of 18° for different shape of particle with bed weight of 500g

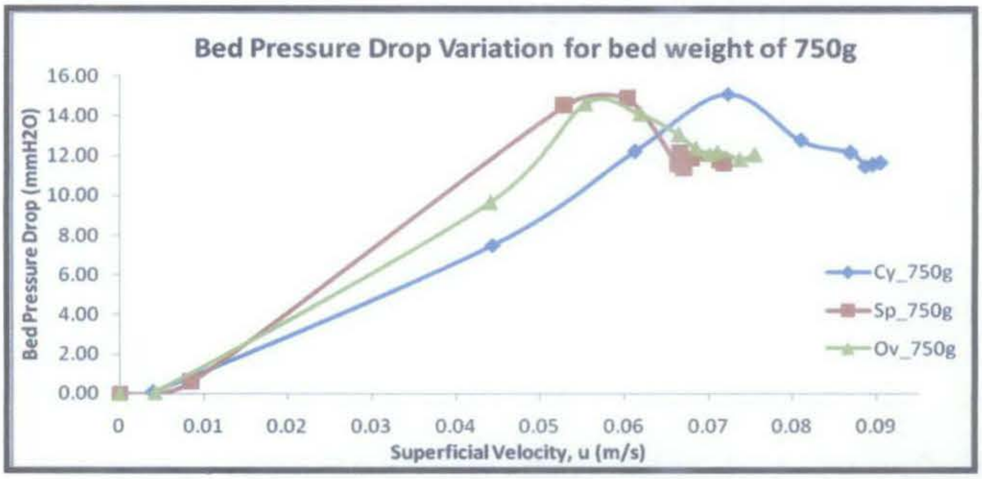


Figure 32: Variation of bed pressure drop with $V_{Superficial}$ with blade overlap angle of 18° for different shape of particle with bed weight of 750g

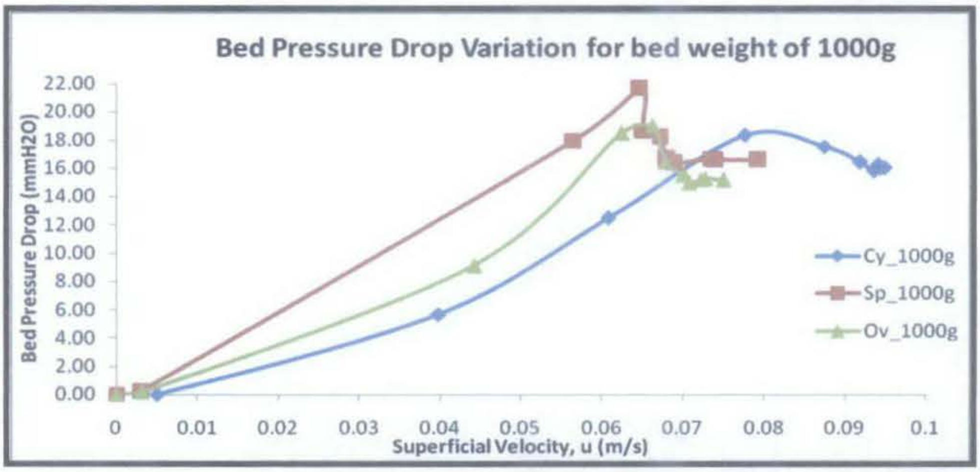


Figure 33: Variation of bed pressure drop with $V_{Superficial}$ with blade overlap angle of 18° for different shape of particle with bed weight of 1000g

4.1.2 Effect of Distributor Blade Angle on Bed Pressure Drop

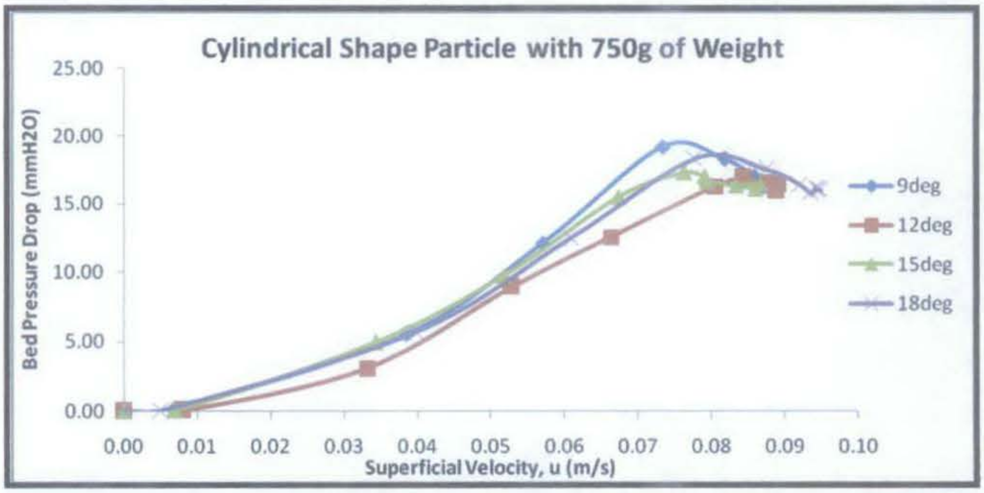


Figure 34: Variation of bed pressure drop with $V_{Superficial}$ for cylindrical shape particle for bed weight of 750g with different distributor overlap angles

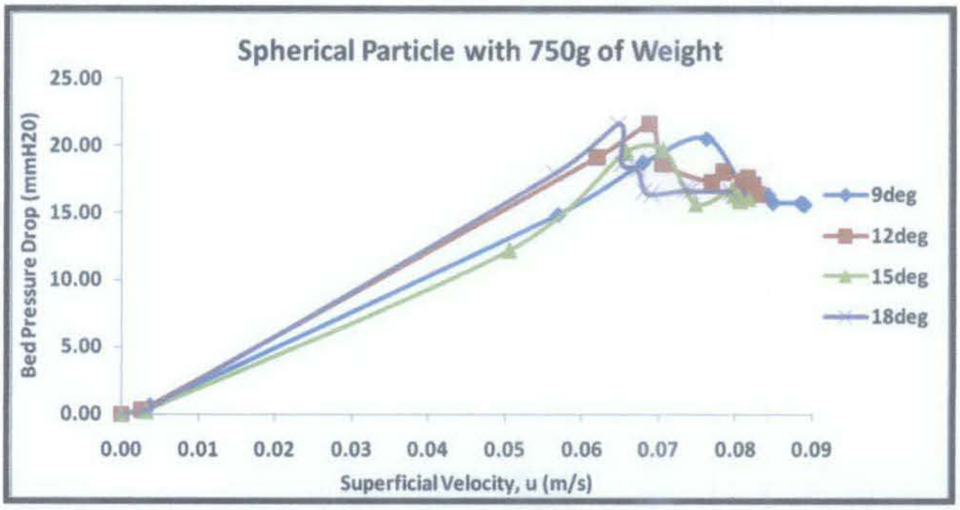


Figure 35: Variation of bed pressure drop with $V_{Superficial}$ for spherical shape particle for bed weight of 750g with different distributor overlap angles

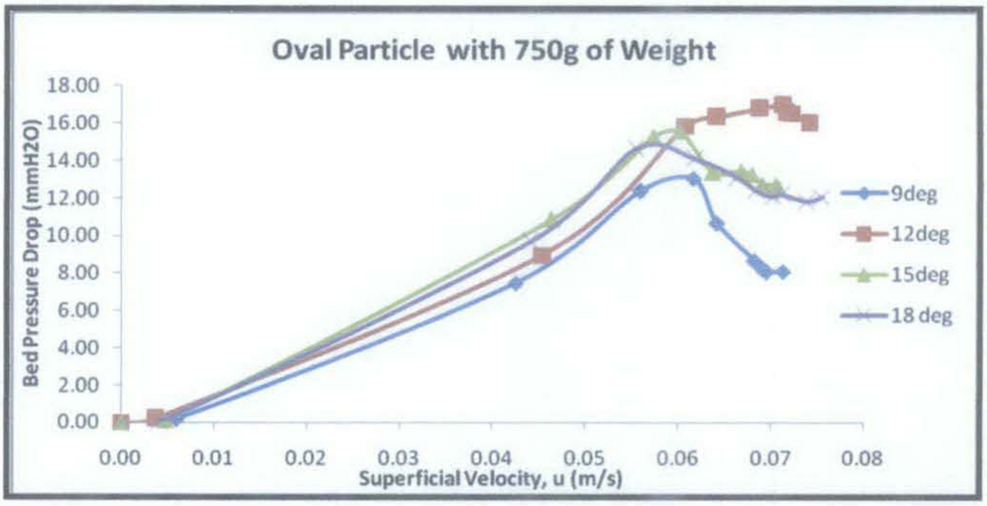


Figure 36: Variation of bed pressure drop with $V_{Superficial}$ for Oval shape particle for bed weight of 750g with different distributor overlap angles

4.1.3 Effect of Bed Weights on Bed Pressure Drop

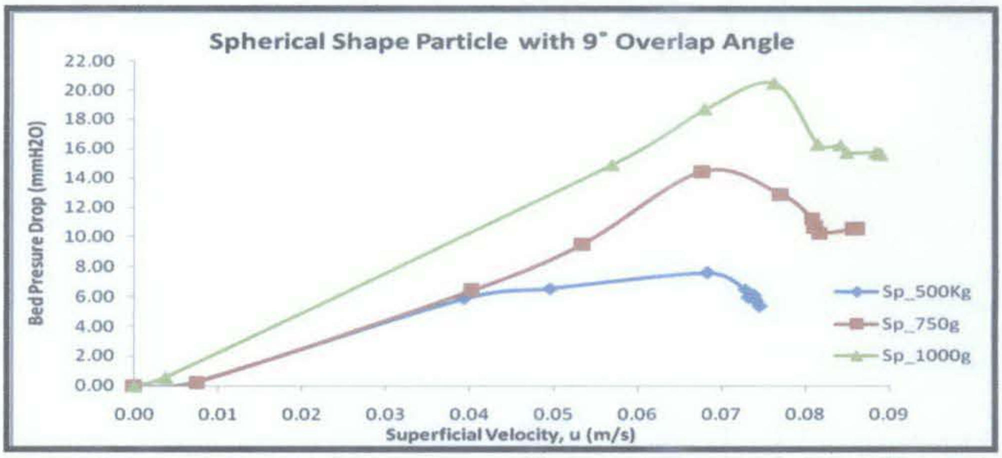


Figure 37: Variation of bed pressure drop with $V_{Superficial}$ for different bed weights with spherical shape particle and blade overlap angle of 9°

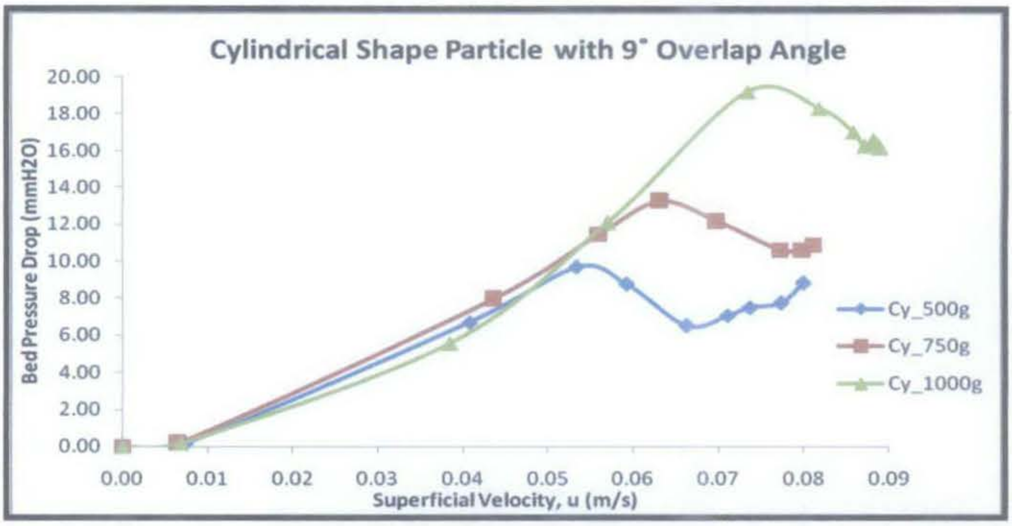


Figure 38: Variation of bed pressure drop with $V_{Superficial}$ for different bed weights with cylindrical shape particle and blade overlap angle of 9°

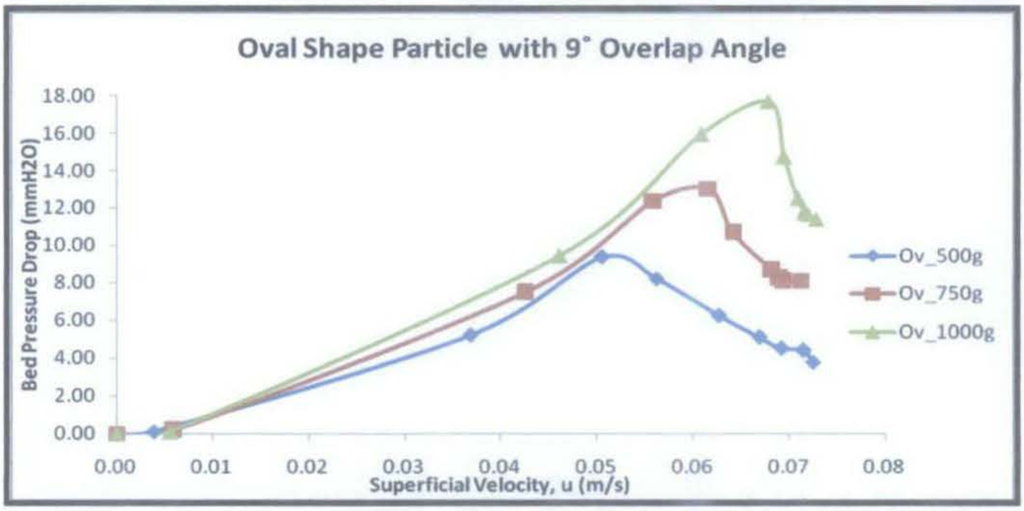


Figure 39: Variation of bed pressure drop with $V_{Superficial}$ for different bed weights with oval shape particle and blade overlap angle of 9°

4.2 Discussions

4.2.1. Effect of Particle Shape on Bed Pressure Drop

There were three different geometry of particle used in this study, which are cylindrical, spherical and oval shape. Four distributor blade overlap angles (9°, 12°, 15° and 18°) were utilized with three different bed loadings (500g, 750g and 1000g) to analyze the influence of particle shape. The effects of these three shapes on bed pressure drop were shown in Figure 22 until Figure 33. For each distributor blade overlap angle, three graphs are provided, where one graph for each bed load. From the analysis, spherical shape has the highest bed pressure drop followed by cylindrical and oval shape particles for blade overlap angle of 9°. Besides that, oval shape particle has the lowest minimum fluidization velocity as compared to cylindrical and spherical particle. The bed pressure drop also increases as the bed weight increases.

On the other hand, for blade overlap angle of 12°, the plots show a mix variation of effect. At first, cylindrical particle has the highest bed pressure drop for bed weight of 500g (Figure 25). Then, oval particle was the highest for 750g bed weight in Figure 26. Lastly, for 1000g bed weight was spherical shape particle (Figure 27). However, spherical particle has the lowest minimum fluidization velocity in all three bed weights.

For 15° overlap angle, cylindrical shape particle has the highest bed pressure drop for 500g and 700g bed weights. Meanwhile, spherical particle was the highest for 1000g. Other than that, oval and spherical particle has the lowest minimum fluidization velocity and the values are closer to each others. But, cylindrical particle fluidized late compared to oval and spherical particle.

Lastly, spherical has the highest bed pressure drop followed by cylindrical and oval particle for the largest blade overlap angle, which is 18°. Again, minimum fluidization velocity is almost same for both oval and spherical particle but highest for cylindrical. Bed pressure drop also increases as the bed weight increases. Same goes for minimum fluidization velocity.

On the whole, spherical particle has the highest bed pressure drop among the three shapes of particle. The higher pressure drop in case of spherical particle is due to a higher energy required to fluidize them. The reason for this may be the uninterrupted or smoother flow across the spherical particle which only generates a lower drag. On the other hand, cylindrical particle has lower bed pressure drop throughout, for all the four blade overlap angles. This may be due to the fact that larger particles are capable of withstanding higher superficial velocity. (Faizal et al, 2010). Besides that, the bed pressure drop is also seen to be consistent in cylindrical particle as compared to spherical and oval. The plots also suggest that cylindrical particle requires a higher velocity for fluidization and hence fluidizes late.

4.2.2 Effect of Distributor Blade Overlap Angle on Bed Pressure Drop

Four different distributor blade overlap angles were utilized to study its influence on bed pressure drop. The four angles were 9°, 12°, 15° and 18°. Three different shapes of particle (cylindrical, oval and spherical) were used in this experiment in order to know which blade overlap angle affect bed pressure drop the most in different shape of particle. Therefore, the author chooses bed weight of 750g for all three shapes of particle to be presented (Figure 34 until Figure 36).

From the analysis of the plots drawn, the bed pressure drop is the highest for 9° blade overlap angle in spherical and cylindrical particle. But for oval shape particle, 12° blade overlap angle shows the highest bed pressure drop. In case of minimum fluidization velocity, oval particle has the lowest value followed by spherical particle in all four blade overlap angles. Again, cylindrical particle fluidized late in all four blade overlap angles as shown in Figure 34.

In general, the bed pressure drop is more for distributor blade overlap angle of 9° as compared to other angles. This is due to more swirling in case of 9° blade overlap angle will attenuate the flow more and consume more energy thereby creating more pressure drop. (Vinod et al., 2011).

4.2.3 Observations

There were few observations monitored while conducting the experiment as well as from the graphs drawn. First of all is the bed behavior. Following regimes were observed as the flow rate is increased progressively as stated by Sreenivasan and Raghavan (2002).

a. Bubbling
b. Wave motion with dune formation
c. Two-layer fluidization
d. Stable swirling

At wave motion with dune formation regime, a localize swirl motion is initiated at any random location in the bed. Then, the swirl extends over certain arc of the bed, while the remaining arc is static. Meanwhile, on the other periphery of static zone, the particle gets lessen due to the same swirling zone. Hence, the bed height is reduced at the periphery which triggers a second swirl motion. Eventually, this behavior of the bed causes the static region grows at one end of swirling arc and decays at the other end. (Sreenivasan and Raghavan, 2002).

For two-layer fluidization regime, there was a thin continuously swirling lower layer and a vigorously bubbling top later were monitored. When the air velocity further increased the dune formation is attenuated, the swirling region gets wider and eventually a fully swirling bed can be observed. These regimes can be clearly observed for cylindrical and oval particles. But, it was hard to observe in spherical particle due to vigorous swirling.

Secondly, the experiment results showed that, the bed pressure drop increases progressively with superficial velocity attaining a maximum or peak and then drops till it becomes stable. Other than that, the bed pressure drop is seen to increase when the bed weight is increased in all the cases, which is attributed to an increase in centrifugal bed weight. (Raghavan et al., 2004). The reason for fall in bed pressure drop after reaching peak is due to the fact that the bed pressure drop will fall as the resistance from the bed decreases. The resistance from the bed decreases as the bed starts fluidized and once fully fluidized the resistance falls greatly since the particles no longer resist the flow. However, it gets mixed with fluid and starts moving and flowing like a fluid. (Vinod et al., 2011).

The peak in bed pressure drop is caused by the additional energy needed to rearrange the 'locked' particles in the bed. Hence, the packed bed slowly fluidized and expands. The particles are lifted up and cause the bed pressure to drop.

Lastly, the minimum fluidization velocity is lower for oval shape particle in all the cases. This is because oval particles have larger exposed surface area compared to the other two shapes hence more drag exerted so gets fluidized quickly.

CHAPTER 5
CONCLUSION AND RECOMMENDATION

5.1 Conclusion

Both particle shape and distributor blade overlap angle have influence on bed pressure drop. The bed pressure drop increases as the superficial velocity increases. Since, bed pressure drop is proportional to the centrifugal weight of the bed; it increases with air velocity in the swirling mode. The trend shown in the results agrees with the expectations based on the theories. Meanwhile, the peak in bed pressure drop is due to the extra energy needed to unlock the particles in the bed.

As a conclusion, spherical particle has the highest bed pressure drop as compared to cylindrical and oval particle. Distributor blade overlap angle of 9° affected the bed pressure drop the most compared to blade overlap angle of 12°, 15° and 18°. Meanwhile, oval particle has the lowest minimum fluidization velocity due to its larger exposed surface area compared to spherical and cylindrical particle. The results obtained not only show superiority of Swirling Fluidized Bed (SFB) over conventional bed but also helped the author to draw conclusion on the effect of the aspects discussed on the bed pressure drop. This research has successfully met its objectives.

5.2 Recommendation

The recommendation is to further investigate the effect of particle shape and distributor blade overlap angle on bed pressure drop. The shapes used in this experiment were uniform in shape. The author would like to recommend using non uniform particle to study the effect of it on the bed pressure drop. In real industrial processes, the particles used normally are non uniform.

Hysteresis effect of bed pressure drop also can be studied in this research. This can be done by taking velocity in reverse direction. Various shapes or particle also can be utilized in this study together with different distributor blade overlap angles. Therefore, there are plenty of research opportunities in bed pressure drop yet to be explored.

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APPENDICES

Sample Excel Sheet Calculations for Blade Overlap Angle of 9°

Cylindrical Particle

Shape: Cyclindrical
Size of Bead :
Bed Weight: 500g
Bed Overlap: 9°
Blade Inclination: 10°

Sl No	Δp in orifice (mmH2O)		Δp Air (mH2O)		C_d	Orifice area, a_2 (m2)	d/D	Flow (m3/sec)		Bed area in (m2)	u (m/sec)		Distributor Δp (mmH2O)		Distributor Δp + Bed Δp (mmH2O)		Bed Δp (mmH2O)	
	F	R	F	R				F	R		F	R	F	R	F	R	F	R
1	0.00	0.00	0.000	0.000	0.668	0.003018	0.620	0.000000	0.000000	0.628	0.0000	0.0000	0.00	0.00	0.00	0.00	0.00	0.00
2	0.28	0.27	0.233	0.225	0.668	0.003018	0.620	0.004672	0.004588	0.628	0.0074	0.0073	0.27	0.38	0.42	0.44	0.15	0.06
3	8.41	3.77	7.008	3.142	0.668	0.003018	0.620	0.025604	0.017143	0.628	0.0408	0.0273	3.66	3.68	10.34	5.22	6.68	1.54
4	14.39	9.92	11.992	8.267	0.668	0.003018	0.620	0.033492	0.027808	0.628	0.0533	0.0443	8.59	8.88	18.25	13.44	9.66	4.56
5	17.75	16.70	14.792	13.917	0.668	0.003018	0.620	0.037197	0.036080	0.628	0.0592	0.0575	15.64	17.35	24.40	25.23	8.76	7.88
6	22.22	24.20	18.517	20.167	0.668	0.003018	0.620	0.041618	0.043433	0.628	0.0663	0.0692	29.04	30.24	35.55	39.32	6.51	9.08
7	25.56	26.70	21.300	22.250	0.668	0.003018	0.620	0.044636	0.045621	0.628	0.0711	0.0726	36.19	36.47	43.25	45.35	7.06	8.88
8	27.49	27.66	22.908	23.050	0.668	0.003018	0.620	0.046291	0.046434	0.628	0.0737	0.0739	39.19	39.16	46.68	48.31	7.49	9.15
9	30.25	28.55	25.208	23.792	0.668	0.003018	0.620	0.048559	0.047175	0.628	0.0773	0.0751	39.74	39.84	47.47	48.89	7.73	9.05
10	32.33	26.37	26.942	21.975	0.668	0.003018	0.620	0.050201	0.045338	0.628	0.0799	0.0722	39.66	39.59	48.48	48.66	8.82	9.07
11	29.88	29.88	24.900	24.900	0.668	0.003018	0.620	0.048261	0.048261	0.628	0.0768	0.0768	39.25	39.25	48.06	48.06	8.81	8.81

Shape: Cyclindrical
Size of Bead :
Bed Weight: 750g
Bed Overlap: 9°
Blade Inclination: 10°

Sl No	Δp in orifice (mmH2O)		Δp Air (mH2O)		C_d	Orifice area, a_2 (m2)	d/D	Flow (m3/sec)		Bed area in (m2)	u (m/sec)		Distributor Δp (mmH2O)		Distributor Δp + Bed Δp (mmH2O)		Bed Δp (mmH2O)	
	F	R	F	R				F	R		F	R	F	R	F	R	F	R
1	0.00	0.00	0.000	0.000	0.668	0.003018	0.620	0.000000	0.000000	0.628	0.0000	0.0000	0.00	0.00	0.00	0.00	0.00	0.00
2	0.22	0.27	0.183	0.225	0.668	0.003018	0.620	0.004141	0.004588	0.628	0.0066	0.0073	0.27	0.38	0.46	0.44	0.19	0.06
3	9.60	5.56	8.000	4.633	0.668	0.003018	0.620	0.027355	0.020818	0.628	0.0436	0.0332	3.66	3.68	11.62	7.16	7.96	3.48
4	15.86	12.26	13.217	10.217	0.668	0.003018	0.620	0.035161	0.030914	0.628	0.0560	0.0492	8.59	8.88	20.04	15.29	11.45	6.41
5	20.16	21.24	16.800	17.700	0.668	0.003018	0.620	0.039642	0.040690	0.628	0.0631	0.0648	15.64	17.35	28.88	27.27	13.24	9.92
6	24.66	25.35	20.550	21.125	0.668	0.003018	0.620	0.043843	0.044453	0.628	0.0698	0.0708	29.04	30.24	41.18	42.50	12.14	12.26
7	29.66	28.68	24.717	23.900	0.668	0.003018	0.620	0.048083	0.047282	0.628	0.0766	0.0753	36.19	36.47	48.40	48.21	12.21	11.74
8	30.10	29.47	25.083	24.558	0.668	0.003018	0.620	0.048439	0.047929	0.628	0.0771	0.0763	39.19	39.16	49.79	50.49	10.60	11.33
9	32.27	31.56	26.892	26.300	0.668	0.003018	0.620	0.050154	0.049599	0.628	0.0799	0.0790	39.74	39.84	50.35	52.22	10.61	12.38
10	32.68	32.82	27.233	27.350	0.668	0.003018	0.620	0.050472	0.050580	0.628	0.0804	0.0805	39.66	39.59	51.48	50.81	11.82	11.22
11	33.25	33.25	27.708	27.708	0.668	0.003018	0.620	0.050910	0.050910	0.628	0.0811	0.0811	39.25	39.25	50.13	50.13	10.88	10.88

Shape: Cyclindrical
Size of Bead :
Bed Weight: 1Kg
Bed Overlap: 9°
Blade Inclination: 10°

Sl No	Δp in orifice (mmH2O)		Δp Air (mH2O)		C_d	Orifice area, $a_{2(m2)}$	d/D	Flow (m3/sec)		Bed area in (m2)	u (m/sec)		Distributor Δp (mmH2O)		Distributor Δp + Bed Δp (mmH2O)		Bed Δp (mmH2O)	
	F	R	F	R				F	R		F	R	F	R	F	R	F	R
1	0.00	0.00	0.000	0.000	0.668	0.003018	0.620	0.000000	0.000000	0.628	0.0000	0.0000	0.00	0.00	0.00	0.00	0.00	0.00
2	0.24	0.26	0.200	0.217	0.668	0.003018	0.620	0.004325	0.004502	0.628	0.0069	0.0072	0.27	0.38	0.45	0.40	0.18	0.02
3	7.50	6.09	6.250	5.075	0.668	0.003018	0.620	0.024179	0.021788	0.628	0.0385	0.0347	3.66	3.68	9.22	7.66	5.56	3.98
4	16.45	14.34	13.708	11.950	0.668	0.003018	0.620	0.035809	0.033434	0.628	0.0570	0.0532	8.59	8.88	20.68	17.56	12.09	8.68
5	27.23	23.81	22.692	19.842	0.668	0.003018	0.620	0.046071	0.043081	0.628	0.0734	0.0686	15.64	17.35	34.86	30.38	19.22	13.03
6	33.85	33.32	28.208	27.767	0.668	0.003018	0.620	0.051367	0.050964	0.628	0.0818	0.0812	29.04	30.24	47.36	46.37	18.32	16.13
7	37.22	35.86	31.017	29.883	0.668	0.003018	0.620	0.053864	0.052871	0.628	0.0858	0.0842	36.19	36.47	53.22	52.38	17.03	15.91
8	38.36	36.33	31.967	30.275	0.668	0.003018	0.620	0.054682	0.053216	0.628	0.0871	0.0847	39.19	39.16	55.44	54.43	16.25	15.27
9	39.33	38.15	32.775	31.792	0.668	0.003018	0.620	0.055369	0.054533	0.628	0.0882	0.0868	39.74	39.84	56.33	55.86	16.59	16.02
10	39.62	38.33	33.017	31.942	0.668	0.003018	0.620	0.055573	0.054661	0.628	0.0885	0.0870	39.66	39.59	56.03	54.29	16.37	14.70
11	40.06	40.06	33.383	33.383	0.668	0.003018	0.620	0.055881	0.055881	0.628	0.0890	0.0890	39.25	39.25	55.40	55.40	16.15	16.15

Spherical Particle

Shape: Spherical
Size of Bead :
Bed Weight: 500g
Bed Overlap: 9°
Blade Inclination: 10°

SI No	Δp in orifice (mmH2O)		Δp Air (mH2O)		C_d	Orifice area, a_2 (m2)	d/D	Flow (m3/sec)		Bed area in (m2)	u (m/sec)		Distributor Δp (mmH2O)		Distributor Δp + Bed Δp (mmH2O)		Bed Δp (mmH2O)	
	F	R	F	R				F	R		F	R	F	R	F	R	F	R
1	0.00	0.00	0.000	0.000	0.668	0.003018	0.620	0.000000	0.000000	0.628	0.0000	0.0000	0.00	0.00	0.00	0.00	0.00	0.00
2	0.26	0.28	0.217	0.233	0.668	0.003018	0.620	0.004502	0.004672	0.628	0.0072	0.0074	0.27	0.38	0.51	0.45	0.24	0.07
3	7.83	7.49	6.525	6.242	0.668	0.003018	0.620	0.024705	0.024163	0.628	0.0393	0.0385	3.66	3.68	9.55	8.96	5.89	5.28
4	12.44	14.57	10.367	12.142	0.668	0.003018	0.620	0.031140	0.033701	0.628	0.0496	0.0537	8.59	8.88	15.13	16.66	6.54	7.78
5	16.22	19.57	13.517	16.308	0.668	0.003018	0.620	0.035558	0.039057	0.628	0.0566	0.0622	15.64	17.35	22.08	25.24	6.44	7.89
6	23.61	24.54	19.675	20.450	0.668	0.003018	0.620	0.042900	0.043737	0.628	0.0683	0.0696	29.04	30.24	36.64	35.48	7.60	5.24
7	26.77	27.46	22.308	22.883	0.668	0.003018	0.620	0.045681	0.046266	0.628	0.0727	0.0737	36.19	36.47	42.68	42.04	6.49	5.57
8	27.10	25.82	22.583	21.517	0.668	0.003018	0.620	0.045961	0.044863	0.628	0.0732	0.0714	39.19	39.16	45.15	44.98	5.96	5.82
9	27.55	26.75	22.958	22.292	0.668	0.003018	0.620	0.046341	0.045664	0.628	0.0738	0.0727	39.74	39.84	45.88	45.68	6.14	5.84
10	27.75	27.37	23.125	22.808	0.668	0.003018	0.620	0.046509	0.046190	0.628	0.0741	0.0736	39.66	39.59	45.43	45.16	5.77	5.57
11	28.10	28.10	23.417	23.417	0.668	0.003018	0.620	0.046802	0.046802	0.628	0.0745	0.0745	39.25	39.25	44.61	44.61	5.36	5.36

Shape: Spherical
Size of Bead :
Bed Weight: 750g
Bed Overlap: 9°
Blade Inclination: 10°

SI No	Δp in orifice (mmH2O)		Δp Air (mH2O)		C_d	Orifice area, a_2 (m2)	d/D	Flow (m3/sec)		Bed area in (m2)	u (m/sec)		Distributor Δp (mmH2O)		Distributor Δp + Bed Δp (mmH2O)		Bed Δp (mmH2O)	
	F	R	F	R				F	R		F	R	F	R	F	R	F	R
1	0.00	0.00	0.000	0.000	0.668	0.003018	0.620	0.000000	0.000000	0.628	0.0000	0.0000	0.00	0.00	0.00	0.00	0.00	0.00
2	0.28	0.23	0.233	0.192	0.668	0.003018	0.620	0.004672	0.004234	0.628	0.0074	0.0067	0.27	0.38	0.51	0.56	0.24	0.18
3	8.16	12.43	6.800	10.358	0.668	0.003018	0.620	0.025220	0.031127	0.628	0.0402	0.0496	3.66	3.68	10.04	14.38	6.38	10.70
4	14.44	19.99	12.033	16.658	0.668	0.003018	0.620	0.033550	0.039474	0.628	0.0534	0.0629	8.59	8.88	18.12	23.33	9.53	14.45
5	23.17	25.32	19.308	21.100	0.668	0.003018	0.620	0.042498	0.044426	0.628	0.0677	0.0707	15.64	17.35	30.09	31.35	14.45	14.00
6	30.02	31.88	25.017	26.567	0.668	0.003018	0.620	0.048374	0.049850	0.628	0.0770	0.0794	29.04	30.24	41.95	42.17	12.91	11.93
7	32.98	32.49	27.483	27.075	0.668	0.003018	0.620	0.050703	0.050325	0.628	0.0807	0.0801	36.19	36.47	47.43	47.28	11.24	10.81
8	33.35	33.81	27.792	28.175	0.668	0.003018	0.620	0.050987	0.051337	0.628	0.0812	0.0817	39.19	39.16	49.82	49.99	10.63	10.83
9	33.70	34.20	28.083	28.500	0.668	0.003018	0.620	0.051253	0.051632	0.628	0.0816	0.0822	39.74	39.84	50.00	50.54	10.26	10.70
10	37.08	36.64	30.900	30.533	0.668	0.003018	0.620	0.053762	0.053442	0.628	0.0856	0.0851	39.66	39.59	50.17	50.29	10.51	10.70
11	37.56	37.56	31.300	31.300	0.668	0.003018	0.620	0.054109	0.054109	0.628	0.0862	0.0862	39.25	39.25	49.77	49.77	10.52	10.52

Shape:Spherical
Size of Bead :
Bed Weight: 1Kg
Bed Overlap: 9°
Blade Inclination: 10°

SI No	Δp in orifice (mmH2O)		Δp Air (mH2O)		C_d	Orifice area, a_2 (m2)	d/D	Flow (m3/sec)		Bed area in (m2)	u (m/sec)		Distributor Δp (mmH2O)		Distributor Δp + Bed Δp (mmH2O)		Bed Δp (mmH2O)	
	F	R	F	R				F	R		F	R	F	R	F	R	F	R
1	0.00	0.00	0.000	0.000	0.668	0.003018	0.620	0.000000	0.000000	0.628	0.0000	0.0000	0.00	0.00	0.00	0.00	0.00	0.00
2	0.07	0.27	0.058	0.225	0.668	0.003018	0.620	0.002336	0.004588	0.628	0.0037	0.0073	0.27	0.38	0.85	0.70	0.58	0.32
3	16.40	12.23	13.667	10.192	0.668	0.003018	0.620	0.035754	0.030876	0.628	0.0569	0.0492	3.66	3.68	18.56	14.27	14.90	10.59
4	23.35	22.27	19.458	18.558	0.668	0.003018	0.620	0.042663	0.041665	0.628	0.0679	0.0663	8.59	8.88	27.30	26.27	18.71	17.39
5	29.38	29.32	24.483	24.433	0.668	0.003018	0.620	0.047856	0.047807	0.628	0.0762	0.0761	15.64	17.35	36.15	36.45	20.51	19.10
6	33.57	31.78	27.975	26.483	0.668	0.003018	0.620	0.051155	0.049772	0.628	0.0815	0.0793	29.04	30.24	45.35	46.21	16.31	15.97
7	35.86	34.44	29.883	28.700	0.668	0.003018	0.620	0.052871	0.051813	0.628	0.0842	0.0825	36.19	36.47	52.47	52.37	16.28	15.90
8	36.43	37.40	30.358	31.167	0.668	0.003018	0.620	0.053289	0.053994	0.628	0.0849	0.0860	39.19	39.16	54.97	54.86	15.78	15.70
9	39.53	37.64	32.942	31.367	0.668	0.003018	0.620	0.055510	0.054167	0.628	0.0884	0.0863	39.74	39.84	55.50	55.27	15.76	15.43
10	39.85	39.38	33.208	32.817	0.668	0.003018	0.620	0.055734	0.055405	0.628	0.0887	0.0882	39.66	39.59	55.33	54.95	15.67	15.36
11	40.04	40.04	33.367	33.367	0.668	0.003018	0.620	0.055867	0.055867	0.628	0.0890	0.0890	39.25	39.25	54.88	54.88	15.63	15.63

Oval Particle

Shape:Oval
Size of Bead :
Bed Weight: 500g
Bed Overlap: 9'
Blade Inclination: 10'

Sl No	Δp in orifice (mmH2O)		Δp Air (mH2O)		C_d	Orifice area, a_2 (m2)	d/D	Flow (m3/sec)		Bed area in (m2)	u (m/sec)		Distributor Δp (mmH2O)		Distributor Δp + Bed Δp (mmH2O)		Bed Δp (mmH2O)	
	F	R	F	R				F	R		F	R	F	R	F	R	F	R
1	0.00	0.00	0.000	0,000	0.668	0.003018	0.620	0.000000	0.000000	0.628	0.0000	0.0000	0.00	0.00	0.00	0.00	0.00	0.00
2	0.08	0.23	0.067	0.192	0.668	0.003018	0.620	0.002497	0.004234	0.628	0.0040	0.0067	0.27	0.38	0.38	0.40	0.11	0.02
3	6.89	5.88	5.742	4.900	0.668	0.003018	0.620	0.023175	0.021409	0.628	0.0369	0.0341	3.66	3.68	8.87	7.52	5.21	3.84
4	12.96	12.26	10.800	10.217	0.668	0.003018	0.620	0.031784	0.030914	0.628	0.0506	0.0492	8.59	8.88	17.96	15.50	9.37	6.62
5	15.99	17.11	13.325	14.258	0.668	0.003018	0.620	0.035305	0.036520	0.628	0.0562	0.0582	15.64	17.35	23.87	23.20	8.23	5.85
6	19.93	20.33	16.608	16.942	0.668	0.003018	0.620	0.039415	0.039809	0.628	0.0628	0.0634	29.04	30.24	35.28	34.35	6.24	4.11
7	22.66	21.24	18.883	17.700	0.668	0.003018	0.620	0.042028	0.040690	0.628	0.0669	0.0648	36.19	36.47	41.30	40.83	5.11	4.36
8	24.24	24.61	20.200	20.508	0.668	0.003018	0.620	0.043468	0.043799	0.628	0.0692	0.0697	39.19	39.16	43.71	43.67	4.52	4.51
9	25.87	25.21	21.558	21.008	0.668	0.003018	0.620	0.044906	0.044330	0.628	0.0715	0.0706	39.74	39.84	44.16	43.97	4.42	4.13
10	26.61	26.61	22.175	22.175	0.668	0.003018	0.620	0.045544	0.045544	0.628	0.0725	0.0725	39.66	39.66	43.45	43.45	3.79	3.79

Shape:Oval
Size of Bead :
Bed Weight: 750g
Bed Overlap: 9'
Blade Inclination: 10'

Sl No	Δp in orifice (mmH2O)		Δp Air (mH2O)		C_d	Orifice area, a_2 (m2)	d/D	Flow (m3/sec)		Bed area in (m2)	u (m/sec)		Distributor Δp (mmH2O)		Distributor Δp + Bed Δp (mmH2O)		Bed Δp (mmH2O)	
	F	R	F	R				F	R		F	R	F	R	F	R	F	R
1	0.00	0.00	0.000	0.000	0.668	0.003018	0.620	0.000000	0.000000	0.628	0.0000	0.0000	0.00	0.00	0.00	0.00	0.00	0.00
2	0.18	0.25	0.150	0.208	0.668	0.003018	0.620	0,003746	0.004414	0.628	0.0060	0.0070	0.27	0.38	0.45	0.38	0.18	0.00
3	9.17	7.98	7.642	6.650	0.668	0.003018	0.620	0.026736	0.024941	0.628	0.0426	0.0397	3.66	3.68	11.14	9.75	7.48	6.07
4	15.83	16.13	13.192	13.442	0.668	0.003018	0.620	0.035128	0.035459	0.628	0.0559	0.0565	8.59	8.88	20.98	20.17	12.39	11.29
5	19.22	20.31	16.017	16.925	0.668	0.003018	0.620	0.038707	0.039789	0.628	0.0616	0.0634	15.64	17.35	28.68	28.18	13.04	10.83
6	20.84	21.39	17.367	17.825	0.668	0.003018	0.620	0,040305	0.040833	0.628	0.0642	0.0650	29.04	30.24	39.73	39.51	10.69	9.27
7	23.55	22.85	19.625	19.042	0.668	0.003018	0.620	0.042845	0.042204	0.628	0.0682	0.0672	36.19	36.47	44.88	44.91	8.69	8.44
8	24.11	23.18	20.092	19.317	0.668	0.003018	0.620	0.043352	0.042507	0.628	0.0690	0.0677	39.19	39.16	47.44	47.59	8.25	8.43
9	24.44	24.94	20.367	20.783	0.668	0.003018	0.620	0.043647	0.044092	0.628	0.0695	0.0702	39.74	39.84	47.83	47.96	8.09	8.12
10	25.70	25.70	21.417	21.417	0.668	0.003018	0.620	0.044758	0.044758	0.628	0.0713	0.0713	39.66	39.66	47.76	47.76	8.10	8.10

Shape: Oval
Size of Bead :
Bed Weight: 1Kg
Bed Overlap: 9'
Blade Inclination: 10'

Sl No	Δp in orifice (mmH2O)		Δp Air (mH2O)		C_d	Orifice area, a_2 (m2)	d/D	Flow (m3/sec)		Bed area in (m2)	u (m/sec)		Distributor Δp (mmH2O)		Distributor Δp + Bed Δp (mmH2O)		Bed Δp (mmH2O)	
	F	R	F	R				F	R		F	R	F	R	F	R	F	R
1	0.00	0.00	0.000	0.000	0.668	0.003018	0.620	0.000000	0.000000	0.628	0.0000	0.0000	0.00	0.00	0.00	0.00	0.00	0.00
2	0.16	0.13	0.133	0.108	0.668	0.003018	0.620	0.003532	0.003183	0.628	0.0056	0.0051	0.27	0.38	0.38	0.45	0.11	0.07
3	10.77	8.00	8.975	6.667	0.668	0.003018	0.620	0.028975	0.024972	0.628	0.0461	0.0398	3.66	3.68	13.10	9.82	9.44	6.14
4	18.75	18.78	15.625	15.650	0.668	0.003018	0.620	0.038230	0.038261	0.628	0.0609	0.0609	8.59	8.88	24.53	22.68	15.94	13.80
5	23.32	24.17	19.433	20.142	0.668	0.003018	0.620	0.042636	0.043406	0.628	0.0679	0.0691	15.64	17.35	33.32	32.05	17.68	14.70
6	24.44	24.76	20.367	20.633	0.668	0.003018	0.620	0.043647	0.043932	0.628	0.0695	0.0700	29.04	30.24	43.79	43.05	14.75	12.81
7	25.45	25.24	21.208	21.033	0.668	0.003018	0.620	0.044540	0.044356	0.628	0.0709	0.0706	36.19	36.47	48.71	48.39	12.52	11.92
8	25.99	25.70	21.658	21.417	0.668	0.003018	0.620	0.045010	0.044758	0.628	0.0717	0.0713	39.19	39.16	50.94	50.82	11.75	11.66
9	26.19	26.34	21.825	21.950	0.668	0.003018	0.620	0.045183	0.045312	0.628	0.0719	0.0722	39.74	39.84	51.43	51.28	11.69	11.44
10	26.86	26.86	22.383	22.383	0.668	0.003018	0.620	0.045757	0.045757	0.628	0.0729	0.0729	39.66	39.66	51.08	51.08	11.42	11.42

Sample Excel Sheet Calculations for Blade Overlap Angle of 12°

Cylindrical Particle

Shape: Cyclindrical
Size of Bead :
Bed Weight: 500g
Bed Overlap: 12°
Blade Inclination: 10°

Sl No	Δp in orifice (mmH2O)		Δp Air (mH2O)		C_d	Orifice area, a_2 (m2)	d/D	Flow (m3/sec)		Bed area in (m2)	u (m/sec)		Distributor Δp (mmH2O)		Distributor Δp + Bed Δp (mmH2O)		Bed Δp (mmH2O)	
	F	R	F	R				F	R		F	R	F	R	F	R	F	R
1	0.00	0.00	0.000	0.000	0.643	0.003018	0.620	0.000000	0.000000	0.628	0.0000	0.0000	0.00	0.00	0.00	0.00	0.00	0.00
2	0.20	0.25	0.167	0.208	0.643	0.003018	0.620	0.003801	0.004249	0.628	0.0061	0.0068	0.19	0.22	0.30	0.25	0.11	0.03
3	13.10	8.02	10.917	6.683	0.643	0.003018	0.620	0.030759	0.024067	0.628	0.0490	0.0383	2.53	2.81	10.55	3.85	8.02	1.04
4	25.30	17.50	21.083	14.583	0.643	0.003018	0.620	0.042747	0.035552	0.628	0.0681	0.0566	5.17	5.18	19.00	7.63	13.83	2.45
5	42.40	38.40	35.333	32.000	0.643	0.003018	0.620	0.055338	0.052663	0.628	0.0881	0.0839	9.75	11.03	24.00	16.08	14.25	5.05
6	72.00	72.60	60.000	60.500	0.643	0.003018	0.620	0.072112	0.072412	0.628	0.1148	0.1153	19.17	19.86	27.77	27.75	8.60	7.89
7	95.30	97.60	79.417	81.333	0.643	0.003018	0.620	0.082964	0.083959	0.628	0.1321	0.1337	25.76	25.83	34.20	34.54	8.44	8.71
8	104.80	105.45	87.333	87.875	0.643	0.003018	0.620	0.087001	0.087270	0.628	0.1385	0.1390	28.05	28.00	36.03	36.79	7.98	8.79
9	108.30	108.28	90.250	90.233	0.643	0.003018	0.620	0.088442	0.088434	0.628	0.1408	0.1408	28.88	28.83	37.40	37.30	8.52	8.47
10	108.40	108.40	90.333	90.333	0.643	0.003018	0.620	0.088483	0.088483	0.628	0.1409	0.1409	29.15	29.15	37.70	37.71	8.55	8.56

Shape: Cyclindrical
Size of Bed :
Bed Weight: 750g
Bed Overlap: 12°
Blade Inclination: 10°

Sl No	Δp in orifice (mmH2O)		Δp Air (mH2O)		C_d	Orifice area, a_2 (m2)	d/D	Flow (m3/sec)		Bed area in (m2)	u (m/sec)		Distributor Δp (mmH2O)		Distributor Δp + Bed Δp (mmH2O)		Bed Δp (mmH2O)	
	F	R	F	R				F	R		F	R	F	R	F	R	F	R
1	0	0	0.000	0.000	0.668	0.003018	0.620	0.000000	0	0.628	0.0000	0.0000	0	0	0	0	0.00	0.00
2	0.18	0.31	0.150	0.258	0.668	0.003018	0.620	0.003746	0.0049157	0.628	0.0060	0.0078	0.34	0.34	0.34	0.34	0.00	0.00
3	4.64	4.20	3.867	3.500	0.668	0.003018	0.620	0.019018	0.0180939	0.628	0.0303	0.0288	3.92	4.23	5.97	5.42	2.05	1.19
4	10.16	10.78	8.467	8.983	0.668	0.003018	0.620	0.028142	0.028988	0.628	0.0448	0.0462	8.44	8.48	13.78	14.00	5.34	5.52
5	17.50	18.72	14.583	15.600	0.668	0.003018	0.620	0.036934	0.0381998	0.628	0.0588	0.0608	15.73	15.79	24.56	24.63	8.83	8.84
6	26.53	29.70	22.108	24.750	0.668	0.003018	0.620	0.045475	0.0481157	0.628	0.0724	0.0766	28.25	28.57	41.13	39.86	12.88	11.29
7	31.45	33.66	26.208	28.050	0.668	0.003018	0.620	0.049513	0.051223	0.628	0.0788	0.0816	34.45	34.72	46.77	46.28	12.32	11.56
8	32.76	32.41	27.300	27.008	0.668	0.003018	0.620	0.050534	0.0502629	0.628	0.0805	0.0800	37.40	37.57	49.66	48.14	12.26	10.57
9	31.68	32.52	26.400	27.100	0.668	0.003018	0.620	0.049694	0.0503482	0.628	0.0791	0.0802	37.93	37.89	50.02	49.23	12.09	11.34
10	29.86	29.86	24.883	24.883	0.668	0.003018	0.620	0.048245	0.0482451	0.628	0.0768	0.0768	37.99	37.99	50.14	50.14	12.15	12.15

Shape: Cyclindrical
Size of Bed :
Bed Weight: 1Kg
Bed Overlap: 12°
Blade Inclination: 10°

Sl No	Δp in orifice (mmH2O)		Δp Air (mH2O)		C_d	Orifice area, a_2 (m2)	d/D	Flow (m3/sec)		Bed area in (m2)	u (m/sec)		Distributor Δp (mmH2O)		Distributor Δp + Bed Δp (mmH2O)		Bed Δp (mmH2O)	
	F	R	F	R				F	R		F	R	F	R	F	R	F	R
1	0.00	0.00	0.000	0.000	0.668	0.003018	0.620	0.000000	0.000000	0.628	0.0000	0.0000	0.00	0.00	0.00	0.00	0.00	0.00
2	0.33	0.39	0.275	0.325	0.668	0.003018	0.620	0.005072	0.005514	0.628	0.0081	0.0088	0.34	0.34	0.42	0.50	0.08	0.16
3	5.55	5.29	4.625	4.408	0.668	0.003018	0.620	0.020800	0.020307	0.628	0.0331	0.0323	3.92	4.23	6.99	6.77	3.07	2.54
4	14.11	13.04	11.758	10.867	0.668	0.003018	0.620	0.033164	0.031882	0.628	0.0528	0.0508	8.44	8.48	17.37	16.28	8.93	7.80
5	22.24	22.06	18.533	18.383	0.668	0.003018	0.620	0.041637	0.041468	0.628	0.0663	0.0660	15.73	15.79	28.30	27.45	12.57	11.66
6	32.80	33.47	27.333	27.892	0.668	0.003018	0.620	0.050564	0.051078	0.628	0.0805	0.0813	28.25	28.57	44.54	43.12	16.29	14.55
7	36.08	36.47	30.067	30.392	0.668	0.003018	0.620	0.053032	0.053318	0.628	0.0844	0.0849	34.45	34.72	51.38	50.76	16.93	16.04
8	39.93	37.68	33.275	31.400	0.668	0.003018	0.620	0.055790	0.054196	0.628	0.0888	0.0863	37.40	37.57	53.37	53.03	15.97	15.46
9	40.13	39.27	33.442	32.725	0.668	0.003018	0.620	0.055930	0.055327	0.628	0.0891	0.0881	37.93	37.89	54.33	53.53	16.40	15.64
10	38.88	38.88	32.400	32.400	0.668	0.003018	0.620	0.055052	0.055052	0.628	0.0877	0.0877	37.99	37.99	54.50	54.50	16.51	16.51

Spherical Particle

Shape: Spherical
Size of Bed : 1mm
Bed Weight: 500g
Bed Overlap: 12'
Blade Inclination: 10'

Sl No	Δp in orifice (mmH2O)		Δp Air (mH2O)		C_d	Orifice area, a2 (m2)	d/D	Flow (m3/sec)		Bed area in (m2)	u (m/sec)		Distributor Δp (mmH2O)		Distributor Δp + Bed Δp (mmH2O)		Bed Δp (mmH2O)	
	F	R	F	R				F	R		F	R	F	R	F	R	F	R
1	0.00	0.00	0.000	0.000	0.668	0.003018	0.620	0.000000	0.000000	0.628	0.0000	0.0000	0.00	0.00	0.00	0.00	0.00	0.00
2	0.07	0.17	0.058	0.142	0.668	0.003018	0.620	0.002336	0.003640	0.628	0.0037	0.0058	0.34	0.34	0.58	0.66	0.24	0.32
3	9.30	7.96	7.750	6.633	0.668	0.003018	0.620	0.026925	0.024909	0.628	0.0429	0.0397	3.92	4.23	12.11	10.20	8.19	5.97
4	13.86	12.63	11.550	10.525	0.668	0.003018	0.620	0.032869	0.031377	0.628	0.0523	0.0500	8.44	8.48	19.17	17.93	10.73	9.45
5	16.18	16.09	13.483	13.408	0.668	0.003018	0.620	0.035514	0.035415	0.628	0.0566	0.0564	15.73	15.79	24.98	24.21	9.25	8.42
6	18.78	19.90	15.650	16.583	0.668	0.003018	0.620	0.038281	0.039385	0.628	0.0609	0.0627	28.25	28.57	37.63	36.73	9.38	8.16
7	19.54	20.27	16.283	16.892	0.668	0.003018	0.620	0.039027	0.039750	0.628	0.0621	0.0633	34.45	34.72	43.35	42.96	8.90	8.24
8	19.66	22.14	16.383	18.450	0.668	0.003018	0.620	0.039147	0.041543	0.628	0.0623	0.0662	37.40	37.57	45.82	45.81	8.42	8.24
9	20.83	22.22	17.358	18.517	0.668	0.003018	0.620	0.040295	0.041618	0.628	0.0642	0.0663	37.93	37.89	46.52	46.26	8.59	8.37
10	21.23	23.43	17.692	19.525	0.668	0.003018	0.620	0.040680	0.042736	0.628	0.0648	0.0681	37.99	37.96	46.33	46.33	8.34	8.37
11	23.47	23.47	19.558	19.558	0.668	0.003018	0.620	0.042773	0.042773	0.628	0.0681	0.0681	38.04	38.04	45.76	45.76	7.72	7.72

Shape: Spherical
Size of Bed : 1mm
Bed Weight: 750g
Bed Overlap: 12'
Blade Inclination: 10'

Sl No	Δp in orifice (mmH2O)		Δp Air (mH2O)		C_d	Orifice area, a2 (m2)	d/D	Flow (m3/sec)		Bed area in (m2)	u (m/sec)		Distributor Δp (mmH2O)		Distributor Δp + Bed Δp (mmH2O)		Bed Δp (mmH2O)	
	F	R	F	R				F	R		F	R	F	R	F	R	F	R
1	0.00	0.00	0.000	0.000	0.668	0.003018	0.620	0.000000	0.000000	0.628	0.0000	0.000	0.00	0.00	0.00	0.00	0.00	0.00
2	0.04	0.16	0.033	0.133	0.668	0.003018	0.620	0.001766	0.003532	0.628	0.0028	0.006	0.34	0.34	0.72	0.53	0.38	0.19
3	14.99	11.16	12.492	9.300	0.668	0.003018	0.620	0.034183	0.029494	0.628	0.0544	0.047	3.92	4.23	18.52	13.37	14.60	9.14
4	17.47	11.37	14.558	9.475	0.668	0.003018	0.620	0.036902	0.029771	0.628	0.0588	0.047	8.44	8.48	22.85	13.72	14.41	5.24
5	19.95	18.17	16.625	15.142	0.668	0.003018	0.620	0.039435	0.037634	0.628	0.0628	0.060	15.73	15.79	29.04	22.87	13.31	7.08
6	24.67	20.69	20.558	17.242	0.668	0.003018	0.620	0.043852	0.040160	0.628	0.0698	0.064	28.25	28.57	41.22	28.76	12.97	0.19
7	26.66	25.93	22.217	21.608	0.668	0.003018	0.620	0.045587	0.044958	0.628	0.0726	0.072	34.45	34.72	47.74	41.92	13.29	7.20
8	27.25	26.86	22.708	22.383	0.668	0.003018	0.620	0.046088	0.045757	0.628	0.0734	0.073	37.40	37.57	50.20	47.44	12.80	9.87
9	28.14	27.21	23.450	22.675	0.668	0.003018	0.620	0.046835	0.046055	0.628	0.0746	0.073	37.93	37.89	50.77	50.81	12.84	12.92
10	28.24	28.15	23.533	23.458	0.668	0.003018	0.620	0.046918	0.046843	0.628	0.0747	0.075	37.99	37.96	50.58	50.35	12.59	12.39
11	29.98	29.98	24.983	24.983	0.668	0.003018	0.620	0.048342	0.048342	0.628	0.0770	0.077	38.04	38.04	50.03	50.03	11.99	11.99

Shape: Spherical
Size of Bed : 1mm
Bed Weight: 1Kg
Bed Overlap: 12'
Blade Inclination: 10'

Sl No	Δp in orifice (mmH2O)		Δp Air (mH2O)		C_d	Orifice area, a2 (m2)	d/D	Flow (m3/sec)		Bed area in (m2)	u (m/sec)		Distributor Δp (mmH2O)		Distributor Δp + Bed Δp (mmH2O)		Bed Δp (mmH2O)	
	F	R	F	R				F	R		F	R	F	R	F	R	F	R
1	0.00	0.00	0.000	0.000	0.668	0.003018	0.620	0.000000	0.00000	0.628	0.0000	0.0000	0.00	0.00	0.00	0.00	0.00	0.00
2	0.04	0.03	0.033	0.025	0.668	0.003018	0.620	0.001766	0.001529	0.628	0.0028	0.0024	0.34	0.34	0.67	0.62	0.33	0.28
3	19.46	12.60	16.217	10.500	0.668	0.003018	0.620	0.038948	0.03134	0.628	0.0620	0.0499	3.92	4.23	23.06	14.55	19.14	10.32
4	23.88	22.49	19.900	18.742	0.668	0.003018	0.620	0.043144	0.04187	0.628	0.0687	0.0667	8.44	8.48	30.10	26.82	21.66	18.34
5	25.22	26.64	21.017	22.200	0.668	0.003018	0.620	0.044338	0.04557	0.628	0.0706	0.0726	15.73	15.79	34.40	34.61	18.67	18.82
6	29.90	31.38	24.917	26.150	0.668	0.003018	0.620	0.048277	0.049458	0.628	0.0769	0.0788	28.25	28.57	45.56	46.88	17.31	18.31
7	31.07	32.37	25.892	26.975	0.668	0.003018	0.620	0.049213	0.050232	0.628	0.0784	0.0800	34.45	34.72	52.45	52.23	18.00	17.51
8	33.22	32.98	27.683	27.483	0.668	0.003018	0.620	0.050887	0.050703	0.628	0.0810	0.0807	37.40	37.57	54.78	54.88	17.38	17.31
9	33.65	33.11	28.042	27.592	0.668	0.003018	0.620	0.051215	0.050803	0.628	0.0816	0.0809	37.93	37.89	55.44	55.20	17.51	17.31
10	34.27	34.40	28.558	28.667	0.668	0.003018	0.620	0.051685	0.051783	0.628	0.0823	0.0825	37.99	37.96	55.15	55.06	17.16	17.10
11	34.66	34.66	28.883	28.883	0.668	0.003018	0.620	0.051978	0.051978	0.628	0.0828	0.0828	38.04	38.04	54.46	54.46	16.42	16.42

Oval Particle

Shape: Oval
Size of Bead : 2mm
Bed Weight: 500g
Bed Overlap: 12°
Blade Inclination: 10°

Sl No	Δp in orifice (mmH2O)		Δp Air (mH2O)		C_d	Orifice area, a2 (m2)	d/D	Flow (m3/sec)		Bed area in (m2)	u (m/sec)		Distributor Δp (mmH2O)		Distributor Δp + Bed Δp (mmH2O)		Bed Δp (mmH2O)	
	F	R	F	R				F	R		F	R	F	R	F	R	F	R
1	0.00	0.00	0.000	0.000	0.668	0.003018	0.620	0.000000	0.00000	0.628	0.0000	0.0000	0.00	0.00	0.00	0.00	0.00	0.00
2	0.15	0.11	0.125	0.092	0.668	0.003018	0.620	0.003419	0.002928	0.628	0.0054	0.0047	0.34	0.34	0.37	0.41	0.03	0.07
3	6.56	6.90	5.467	5.750	0.668	0.003018	0.620	0.022613	0.023192	0.628	0.0360	0.0369	3.92	4.23	8.29	8.65	4.37	4.42
4	14.30	13.68	11.917	11.400	0.668	0.003018	0.620	0.033387	0.032655	0.628	0.0532	0.0520	8.44	8.48	18.77	18.73	10.33	10.25
5	17.28	18.05	14.400	15.042	0.668	0.003018	0.620	0.036701	0.03751	0.628	0.0584	0.0597	15.73	15.79	27.39	27.02	11.66	11.23
6	21.38	21.72	17.817	18.100	0.668	0.003018	0.620	0.040824	0.041147	0.628	0.0650	0.0655	28.25	28.57	40.77	41.24	12.52	12.67
7	23.56	23.27	19.633	19.392	0.668	0.003018	0.620	0.042854	0.04259	0.628	0.0682	0.0678	34.45	34.72	47.76	47.53	13.31	12.81
8	23.65	23.98	19.708	19.983	0.668	0.003018	0.620	0.042936	0.043235	0.628	0.0684	0.0688	37.40	37.57	50.49	50.27	13.09	12.70
9	24.26	24.70	20.217	20.583	0.668	0.003018	0.620	0.043486	0.043879	0.628	0.0692	0.0699	37.93	37.89	50.87	51.01	12.94	13.12
10	25.01	25.01	20.842	20.842	0.668	0.003018	0.620	0.044153	0.044153	0.628	0.0703	0.0703	37.99	37.99	50.55	50.55	12.56	12.56

Shape: Oval
Size of Bed : 2mm
Bed Weight: 750g
Bed Overlap: 12°
Blade Inclination: 10°

Sl No	Δp in orifice (mmH2O)		Δp Air (mH2O)		C_d	Orifice area, a2 (m2)	d/D	Flow (m3/sec)		Bed area in (m2)	u (m/sec)		Distributor Δp (mmH2O)		Distributor Δp + Bed Δp (mmH2O)		Bed Δp (mmH2O)	
	F	R	F	R				F	R		F	R	F	R	F	R	F	R
1	0.00	0.00	0.000	0.000	0.668	0.003018	0.620	0.000000	0.00000	0.628	0.0000	0.0000	0.00	0.00	0.00	0.00	0.00	0.00
2	0.07	0.10	0.058	0.083	0.668	0.003018	0.620	0.002336	0.002792	0.628	0.0037	0.0044	0.34	0.34	0.55	0.50	0.21	0.16
3	10.45	7.61	8.708	6.342	0.668	0.003018	0.620	0.028541	0.024356	0.628	0.0454	0.0388	3.92	4.23	12.88	9.44	8.96	5.21
4	18.74	17.87	15.617	14.892	0.668	0.003018	0.620	0.038220	0.037322	0.628	0.0609	0.0594	8.44	8.48	24.30	22.21	15.86	13.73
5	20.86	22.60	17.383	18.833	0.668	0.003018	0.620	0.040324	0.041972	0.628	0.0642	0.0668	15.73	15.79	32.09	31.10	16.36	15.31
6	23.98	24.33	19.983	20.275	0.668	0.003018	0.620	0.043235	0.043549	0.628	0.0688	0.0693	28.25	28.57	45.07	44.02	16.82	15.45
7	25.74	25.45	21.450	21.208	0.668	0.003018	0.620	0.044793	0.04454	0.628	0.0713	0.0709	34.45	34.72	51.42	51.00	16.97	16.28
8	25.98	26.16	21.650	21.800	0.668	0.003018	0.620	0.045002	0.045157	0.628	0.0717	0.0719	37.40	37.57	53.97	53.58	16.57	16.01
9	26.43	26.97	22.025	22.475	0.668	0.003018	0.620	0.045390	0.045851	0.628	0.0723	0.0730	37.93	37.89	54.49	54.56	16.56	16.67
10	27.81	27.81	23.175	23.175	0.668	0.003018	0.620	0.046560	0.04656	0.628	0.0741	0.0741	37.99	37.99	54.00	54.00	16.01	16.01

Shape: Oval
Size of Bed : 2mm
Bed Weight: 1Kg
Bed Overlap: 12°
Blade Inclination: 10°

Sl No	Δp in orifice (mmH2O)		Δp Air (mH2O)		C_c	Orifice area, a2 (m2)	d/D	Flow (m3/sec)		Bed area in (m2)	u (m/sec)		Distributor Δp (mmH2O)		Distributor Δp + Bed Δp (mmH2O)		Bed Δp (mmH2O)	
	F	R	F	R				F	R		F	R	F	R	F	R	F	R
1	0.00	0.00	0.000	0.000	0.668	0.003018	0.620	0.000000	0.00000	0.628	0.0000	0.0000	0.00	0.00	0.00	0.00	0.00	0.00
2	0.07	0.11	0.058	0.092	0.668	0.003018	0.620	0.002336	0.002928	0.628	0.0037	0.0047	0.34	0.34	0.62	0.41	0.28	0.07
3	11.93	8.99	9.942	7.492	0.668	0.003018	0.620	0.030495	0.026472	0.628	0.0486	0.0422	3.92	4.23	14.65	11.11	10.73	6.88
4	21.63	19.84	18.025	16.533	0.668	0.003018	0.620	0.041062	0.039326	0.628	0.0654	0.0626	8.44	8.48	28.34	25.58	19.90	17.10
5	24.96	25.06	20.800	20.883	0.668	0.003018	0.620	0.044109	0.044198	0.628	0.0702	0.0704	15.73	15.79	36.28	35.87	20.55	20.08
6	25.80	25.24	21.500	21.033	0.668	0.003018	0.620	0.044845	0.044356	0.628	0.0714	0.0706	28.25	28.57	48.61	47.01	20.36	18.44
7	28.86	27.00	24.050	22.500	0.668	0.003018	0.620	0.047430	0.045876	0.628	0.0755	0.0731	34.45	34.72	54.60	54.27	20.15	19.55
8	28.94	28.88	24.117	24.067	0.668	0.003018	0.620	0.047496	0.047447	0.628	0.0756	0.0756	37.40	37.57	57.18	56.97	19.78	19.40
9	29.61	29.68	24.675	24.733	0.668	0.003018	0.620	0.048043	0.048099	0.628	0.0765	0.0766	37.93	37.89	57.66	57.58	19.73	19.69
10	29.71	29.71	24.758	24.758	0.668	0.003018	0.620	0.048124	0.048124	0.628	0.0766	0.0766	37.99	37.99	57.39	57.39	19.40	19.40

Sample Excel Sheet Calculations for Blade Overlap Angle of 15°

Cylindrical Particle

Shape: Cyclindrical
Size of Bed :
Bed Weight: 500g
Bed Overlap: 15°
Blade Inclination: 10°

Sl No	Δp in orifice (mmH2O)		Δp Air (mH2O)		C_d	Orifice area, a_2 (m2)	d/D	Flow (m3/sec)		Bed area in (m2)	u (m/sec)		Distributor Δp (mmH2O)		Distributor Δp + Bed Δp (mmH2O)		Bed Δp (mmH2O)	
	F	R	F	R				F	R		F	R	F	R	F	R	F	R
1	0	0	0.000	0.000	0.668	0.003018	0.620	0.000000	0.000000	0.628	0.0000	0.0000	0	0	0	0	0.00	0.00
2	0.04	0.29	0.033	0.242	0.668	0.003018	0.620	0.001766	0.004755	0.628	0.0028	0.0076	0.34	0.37	0.67	0.44	0.33	0.07
3	12.55	3.62	10.458	3.017	0.668	0.003018	0.620	0.031277	0.016798	0.628	0.0498	0.0267	2.54	2.59	14.66	5.05	12.12	2.46
4	18.66	8.70	15.550	7.250	0.668	0.003018	0.620	0.038139	0.026042	0.628	0.0607	0.0415	7.55	7.48	23.36	11.56	15.81	4.08
5	19.88	15.98	16.567	13.317	0.668	0.003018	0.620	0.039366	0.035294	0.628	0.0627	0.0562	13.64	14.02	26.38	21.27	12.74	7.25
6	22.35	24.08	18.625	20.067	0.668	0.003018	0.620	0.041739	0.043325	0.628	0.0665	0.0690	26.38	25.90	34.24	35.78	7.86	9.88
7	24.77	24.41	20.642	20.342	0.668	0.003018	0.620	0.043941	0.043621	0.628	0.0700	0.0695	32.23	32.32	40.58	42.15	8.35	9.83
8	30.23	25.42	25.192	21.183	0.668	0.003018	0.620	0.048543	0.044514	0.628	0.0773	0.0709	34.98	35.05	44.98	44.88	10.00	9.83
9	31.24	25.55	26.033	21.292	0.668	0.003018	0.620	0.049347	0.044628	0.628	0.0786	0.0711	35.82	35.66	45.06	45.42	9.24	9.76
10	29.24	29.39	24.367	24.492	0.668	0.003018	0.620	0.047742	0.047864	0.628	0.0760	0.0762	35.34	35.51	44.98	45.31	9.64	9.80
11	25.47	25.47	21.225	21.225	0.668	0.003018	0.620	0.044558	0.044558	0.628	0.0710	0.0710	34.92	34.92	44.84	44.84	9.92	9.92

Shape: Cyclindrical
Size of Bed :
Bed Weight: 750g
Bed Overlap: 15°
Blade Inclination: 10°

Sl No	Δp in orifice (mmH2O)		Δp Air (mH2O)		C_d	Orifice area, a_2 (m2)	d/D	Flow (m3/sec)		Bed area in (m2)	u (m/sec)		Distributor Δp (mmH2O)		Distributor Δp + Bed Δp (mmH2O)		Bed Δp (mmH2O)	
	F	R	F	R				F	R		F	R	F	R	F	R	F	R
1	0	0	0.000	0.000	0.668	0.003018	0.620	0.000000	0.000000	0.628	0.0000	0.0000	0	0	0	0	0.00	0.00
2	0.26	0.29	0.217	0.242	0.668	0.003018	0.620	0.004502	0.004502	0.628	0.0072	0.0072	0.34	0.37	0.43	0.44	0.09	0.07
3	9.96	4.32	8.300	3.600	0.668	0.003018	0.620	0.027864	0.027864	0.628	0.0444	0.0444	2.54	2.59	11.66	5.76	9.12	3.17
4	18.52	9.93	15.433	8.275	0.668	0.003018	0.620	0.037995	0.037995	0.628	0.0605	0.0605	7.55	7.48	22.05	12.89	14.50	5.41
5	24.85	18.14	20.708	15.117	0.668	0.003018	0.620	0.044012	0.044012	0.628	0.0701	0.0701	13.64	14.02	31.77	24.18	18.13	10.16
6	26.26	24.26	21.883	20.217	0.668	0.003018	0.620	0.045243	0.045243	0.628	0.0720	0.0720	26.38	25.90	38.68	38.61	12.30	12.71
7	28.67	27.33	23.892	22.775	0.668	0.003018	0.620	0.047274	0.047274	0.628	0.0753	0.0753	32.23	32.32	43.46	44.88	11.23	12.56
8	29.41	29.49	24.508	24.575	0.668	0.003018	0.620	0.047880	0.047880	0.628	0.0762	0.0762	34.98	35.05	46.71	46.69	11.73	11.64
9	29.50	29.82	24.583	24.850	0.668	0.003018	0.620	0.047953	0.047953	0.628	0.0764	0.0764	35.82	35.66	47.25	47.41	11.43	11.75
10	29.61	31.88	24.675	26.567	0.668	0.003018	0.620	0.048043	0.048043	0.628	0.0765	0.0765	35.34	35.51	46.64	47.30	11.30	11.79
11	31.92	31.92	26.600	26.600	0.668	0.003018	0.620	0.049882	0.049882	0.628	0.0794	0.0794	34.92	34.92	46.58	46.58	11.66	11.66

Shape: Cyclindrical
Size of Bed :
Bed Weight: 1Kg
Bed Overlap: 15°
Blade Inclination: 10°

Sl No	Δp in orifice (mmH2O)		Δp Air (mH2O)		C_d	Orifice area, a_2 (m2)	d/D	Flow (m3/sec)		Bed area in (m2)	u (m/sec)		Distributor Δp (mmH2O)		Distributor Δp + Bed Δp (mmH2O)		Bed Δp (mmH2O)	
	F	R	F	R				F	R		F	R	F	R	F	R	F	R
1	0	0	0.000	0.000	0.668	0.003018	0.620	0.000000	0.000000	0.628	0.0000	0.0000	0	0	0	0	0.00	0.00
2	0.24	0.28	0.200	0.233	0.668	0.003018	0.620	0.004325	0.004672	0.628	0.0069	0.0074	0.34	0.37	0.41	0.44	0.07	0.07
3	5.95	4.64	4.958	3.867	0.668	0.003018	0.620	0.021536	0.019018	0.628	0.0343	0.0303	2.54	2.59	7.49	5.99	4.95	3.40
4	13.56	11.32	11.300	9.433	0.668	0.003018	0.620	0.032512	0.029705	0.628	0.0518	0.0473	7.55	7.48	17.28	14.59	9.73	7.11
5	22.99	19.77	19.158	16.475	0.668	0.003018	0.620	0.042333	0.039257	0.628	0.0674	0.0625	13.64	14.02	29.18	26.09	15.54	12.07
6	29.45	28.99	24.542	24.158	0.668	0.003018	0.620	0.047913	0.047537	0.628	0.0763	0.0757	26.38	25.90	43.70	44.00	17.32	18.10
7	31.66	30.72	26.383	25.600	0.668	0.003018	0.620	0.049678	0.048935	0.628	0.0791	0.0779	32.23	32.32	49.24	49.01	17.01	16.69
8	31.89	30.87	26.575	25.725	0.668	0.003018	0.620	0.049858	0.049054	0.628	0.0794	0.0781	34.98	35.05	51.67	51.36	16.69	16.31
9	37.33	32.38	31.108	26.983	0.668	0.003018	0.620	0.053943	0.050240	0.628	0.0859	0.0800	35.82	35.66	51.95	52.22	16.13	16.56
10	37.99	33.02	31.658	27.517	0.668	0.003018	0.620	0.054418	0.050734	0.628	0.0867	0.0808	35.34	35.51	51.87	51.82	16.53	16.31
11	35.12	35.12	29.267	29.267	0.668	0.003018	0.620	0.052322	0.052322	0.628	0.0833	0.0833	34.92	34.92	51.30	51.30	16.38	16.38

Spherical Particle

Shape: Spherical
Size of Bed :
Bed Weight: 500g
Bed Overlap: 15˚
Blade Inclination: 10˚

Sl No	Δp in orifice (mmH2O)		Δp Air (mH2O)		C_d	Orifice area, a_2 (m2)	d/D	Flow (m3/sec)		Bed area in (m2)	u (m/sec)		Distributor Δp (mmH2O)		Distributor Δp + Bed Δp (mmH2O)		Bed Δp (mmH2O)	
	F	R	F	R				F	R		F	R	F	R	F	R	F	R
1	0	0	0.000	0.000	0.668	0.003018	0.620	0.000000	0.000000	0.628	0.0000	0.0000	0	0	0	0	0.00	0.00
2	0.28	0.26	0.233	0.217	0.668	0.003018	0.620	0.004672	0.004502	0.628	0.0074	0.0072	0.34	0.37	0.54	0.42	0.20	0.05
3	6.96	5.75	5.800	4.792	0.668	0.003018	0.620	0.023292	0.021171	0.628	0.0371	0.0337	2.54	2.59	8.92	7.47	6.38	4.88
4	10.93	11.87	9.108	9.892	0.668	0.003018	0.620	0.029189	0.030418	0.628	0.0465	0.0484	7.55	7.48	14.94	15.76	7.39	8.28
5	12.95	15.12	10.792	12.600	0.668	0.003018	0.620	0.031772	0.034331	0.628	0.0506	0.0547	13.64	14.02	22.46	22.85	8.82	8.83
6	16.45	16.40	13.708	13.667	0.668	0.003018	0.620	0.035809	0.035754	0.628	0.0570	0.0569	26.38	25.90	33.12	33.31	6.74	7.41
7	20.36	18.44	16.967	15.367	0.668	0.003018	0.620	0.039838	0.037913	0.628	0.0634	0.0604	32.23	32.32	39.77	39.55	7.54	7.23
8	21.03	20.85	17.525	17.375	0.668	0.003018	0.620	0.040488	0.040315	0.628	0.0645	0.0642	34.98	35.05	42.52	42.38	7.54	7.33
9	21.61	21.55	18.008	17.958	0.668	0.003018	0.620	0.041043	0.040986	0.628	0.0654	0.0653	35.82	35.66	43.02	42.72	7.20	7.06
10	21.75	21.87	18.125	18.225	0.668	0.003018	0.620	0.041175	0.041289	0.628	0.0656	0.0657	35.34	35.51	42.61	42.63	7.27	7.12
11	22.27	22.27	18.558	18.558	0.668	0.003018	0.620	0.041665	0.041665	0.628	0.0663	0.0663	34.92	34.92	42.23	42.23	7.31	7.31

Shape: Spherical
Size of Bed :
Bed Weight: 750g
Bed Overlap: 15˚
Blade Inclination: 10˚

Sl No	Δp in orifice (mmH2O)		Δp Air (mH2O)		C_d	Orifice area, a_2 (m2)	d/D	Flow (m3/sec)		Bed area in (m2)	u (m/sec)		Distributor Δp (mmH2O)		Distributor Δp + Bed Δp (mmH2O)		Bed Δp (mmH2O)	
	F	R	F	R				F	R		F	R	F	R	F	R	F	R
1	0	0	0.000	0.000	0.668	0.003018	0.620	0.000000	0.000000	0.628	0.0000	0.0000	0	0	0	0	0.00	0.00
2	0.11	0.25	0.092	0.208	0.668	0.003018	0.620	0.002928	0.004414	0.628	0.0047	0.0070	0.34	0.37	0.49	0.45	0.15	0.08
3	10.09	7.98	8.408	6.650	0.668	0.003018	0.620	0.028045	0.024941	0.628	0.0447	0.0397	2.54	2.59	12.05	9.54	9.51	6.95
4	17.22	15.32	14.350	12.767	0.668	0.003018	0.620	0.036637	0.034557	0.628	0.0583	0.0550	7.55	7.48	21.73	19.25	14.18	11.77
5	19.84	19.88	16.533	16.567	0.668	0.003018	0.620	0.039326	0.039366	0.628	0.0626	0.0627	13.64	14.02	27.28	27.82	13.64	13.80
6	23.36	23.86	19.467	19.883	0.668	0.003018	0.620	0.042672	0.043126	0.628	0.0679	0.0687	26.38	25.90	38.40	39.11	12.02	13.21
7	25.66	24.77	21.383	20.642	0.668	0.003018	0.620	0.044724	0.043941	0.628	0.0712	0.0700	32.23	32.32	44.12	44.20	11.89	11.88
8	26.45	25.48	22.042	21.233	0.668	0.003018	0.620	0.045407	0.044566	0.628	0.0723	0.0710	34.98	35.05	47.00	47.12	12.02	12.07
9	26.59	26.29	22.158	21.908	0.668	0.003018	0.620	0.045527	0.045269	0.628	0.0725	0.0721	35.82	35.66	47.57	47.55	11.75	11.89
10	27.82	26.66	23.183	22.217	0.668	0.003018	0.620	0.046568	0.045587	0.628	0.0742	0.0726	35.34	35.51	47.17	47.25	11.83	11.74
11	28.25	28.25	23.542	23.542	0.668	0.003018	0.620	0.046926	0.046926	0.628	0.0747	0.0747	34.92	34.92	46.78	46.78	11.86	11.86

Shape: Spherical
Size of Bed :
Bed Weight: 1Kg
Bed Overlap: 15˚
Blade Inclination: 10˚

Sl No	Δp in orifice (mmH2O)		Δp Air (mH2O)		C_d	Orifice area, a_2 (m2)	d/D	Flow (m3/sec)		Bed area in (m2)	u (m/sec)		Distributor Δp (mmH2O)		Distributor Δp + Bed Δp (mmH2O)		Bed Δp (mmH2O)	
	F	R	F	R				F	R		F	R	F	R	F	R	F	R
1	0	0	0.000	0.000	0.668	0.003018	0.620	0.000000	0.000000	0.628	0.0000	0.0000	0	0	0	0	0.00	0.00
2	0.05	0.25	0.042	0.208	0.668	0.003018	0.620	0.001974	0.004414	0.628	0.0031	0.0070	0.34	0.37	0.56	0.44	0.22	0.07
3	12.94	11.27	10.783	9.392	0.668	0.003018	0.620	0.031760	0.029639	0.628	0.0506	0.0472	2.54	2.59	14.72	12.93	12.18	10.34
4	21.86	20.77	18.217	17.308	0.668	0.003018	0.620	0.041279	0.040237	0.628	0.0657	0.0641	7.55	7.48	27.09	24.40	19.54	16.92
5	25.22	27.10	21.017	22.583	0.668	0.003018	0.620	0.044338	0.045961	0.628	0.0706	0.0732	13.64	14.02	33.32	33.64	19.68	19.62
6	28.28	28.50	23.567	23.750	0.668	0.003018	0.620	0.046951	0.047134	0.628	0.0748	0.0751	26.38	25.90	42.09	43.87	15.71	17.97
7	32.08	29.76	26.733	24.800	0.668	0.003018	0.620	0.050006	0.048164	0.628	0.0796	0.0767	32.23	32.32	49.05	49.45	16.82	17.13
8	32.17	29.86	26.808	24.883	0.668	0.003018	0.620	0.050076	0.048245	0.628	0.0797	0.0768	34.98	35.05	51.32	51.02	16.34	15.97
9	32.89	30.33	27.408	25.275	0.668	0.003018	0.620	0.050634	0.048623	0.628	0.0806	0.0774	35.82	35.66	51.90	51.62	16.08	15.96
10	32.91	33.36	27.425	27.800	0.668	0.003018	0.620	0.050649	0.050994	0.628	0.0807	0.0812	35.34	35.51	51.24	51.59	15.90	16.08
11	33.81	33.81	28.175	28.175	0.668	0.003018	0.620	0.051337	0.051337	0.628	0.0817	0.0817	34.92	34.92	51.02	51.02	16.10	16.10

Oval Particle

Shape: Spherical
Size of Bed :
Bed Weight: 1Kg
Bed Overlap: 15'
Blade Inclination: 10'

Sl No	Δp in orifice (mmH2O)		Δp Air (mH2O)		C_d	Orifice area, a_2 (m2)	d/D	Flow (m3/sec)		Bed area in (m2)	u (m/sec)		Distributor Δp (mmH2O)		Distributor Δp + Bed Δp (mmH2O)		Bed Δp (mmH2O)	
	F	R	F	R				F	R		F	R	F	R	F	R	F	R
1	0.00	0.00	0.000	0.000	0.668	0.003018	0.620	0.000000	0.000000	0.628	0.0000	0.0000	0.00	0.00	0.00	0.00	0.00	0.00
2	0.09	0.21	0.075	0.175	0.668	0.003018	0.620	0.002649	0.004046	0.628	0.0042	0.0064	0.34	0.37	0.35	0.38	0.01	0.01
3	4.76	5.52	3.967	4.600	0.668	0.003018	0.620	0.019262	0.020743	0.628	0.0307	0.0330	2.54	2.59	6.44	7.38	3.90	4.79
4	12.77	11.88	10.642	9.900	0.668	0.003018	0.620	0.031550	0.030431	0.628	0.0502	0.0485	7.55	7.48	17.57	16.46	10.02	8.98
5	14.68	13.75	12.233	11.458	0.668	0.003018	0.620	0.033828	0.032739	0.628	0.0539	0.0521	13.64	14.02	23.57	23.33	9.93	9.31
6	17.81	15.98	14.842	13.317	0.668	0.003018	0.620	0.037260	0.035294	0.628	0.0593	0.0562	26.38	25.90	34.88	35.48	8.50	9.58
7	19.80	16.68	16.500	13.900	0.668	0.003018	0.620	0.039286	0.036058	0.628	0.0626	0.0574	32.23	32.32	41.96	41.78	9.73	9.46
8	20.90	18.75	17.417	15.625	0.668	0.003018	0.620	0.040363	0.038230	0.628	0.0643	0.0609	34.98	35.05	44.11	44.31	9.13	9.26
9	22.22	20.39	18.517	16.992	0.668	0.003018	0.620	0.041618	0.039867	0.628	0.0663	0.0635	35.82	35.66	44.83	44.81	9.01	9.15
10	23.42	23.87	19.517	19.892	0.668	0.003018	0.620	0.042727	0.043135	0.628	0.0680	0.0687	35.34	35.51	44.67	44.59	9.33	9.08
11	24.55	24.55	20.458	20.458	0.668	0.003018	0.620	0.043746	0.043746	0.628	0.0697	0.0697	34.92	34.92	44.39	44.39	9.47	9.47

Shape: Oval
Size of Bed :
Bed Weight: 750g
Bed Overlap: 15'
Blade Inclination: 10'

Sl No	Δp in orifice (mmH2O)		Δp Air (mH2O)		C_d	Orifice area, a_2 (m2)	d/D	Flow (m3/sec)		Bed area in (m2)	u (m/sec)		Distributor Δp (mmH2O)		Distributor Δp + Bed Δp (mmH2O)		Bed Δp (mmH2O)	
	F	R	F	R				F	R		F	R	F	R	F	R	F	R
1	0	0	0.000	0.000	0.668	0.003018	0.620	0.000000	0.000000	0.628	0.0000	0.0000	0	0	0	0	0.00	0.00
2	0.12	0.26	0.100	0.217	0.668	0.003018	0.620	0.003058	0.004502	0.628	0.0049	0.0072	0.34	0.37	0.45	0.40	0.11	0.03
3	10.92	7.05	9.100	5.875	0.668	0.003018	0.620	0.029176	0.023442	0.628	0.0465	0.0373	2.54	2.59	13.44	9.08	10.90	6.49
4	16.67	15.40	13.892	12.833	0.668	0.003018	0.620	0.036048	0.034647	0.628	0.0574	0.0552	7.55	7.48	22.82	20.30	15.27	12.82
5	18.32	18.98	15.267	15.817	0.668	0.003018	0.620	0.037789	0.038464	0.628	0.0602	0.0612	13.64	14.02	29.21	28.37	15.57	14.35
6	20.55	20.97	17.125	17.475	0.668	0.003018	0.620	0.040023	0.040430	0.628	0.0637	0.0644	26.38	25.90	39.78	39.57	13.40	13.67
7	22.54	21.69	18.783	18.075	0.668	0.003018	0.620	0.041917	0.041119	0.628	0.0667	0.0655	32.23	32.32	45.65	45.60	13.42	13.28
8	23.36	22.09	19.467	18.408	0.668	0.003018	0.620	0.042672	0.041496	0.628	0.0679	0.0661	34.98	35.05	48.25	47.97	13.27	12.92
9	24.14	23.99	20.117	19.992	0.668	0.003018	0.620	0.043379	0.043244	0.628	0.0691	0.0689	35.82	35.66	48.57	48.37	12.75	12.71
10	25.16	24.52	20.967	20.433	0.668	0.003018	0.620	0.044286	0.043719	0.628	0.0705	0.0696	35.34	35.51	48.05	48.15	12.71	12.64
11	25.37	25.37	21.142	21.142	0.668	0.003018	0.620	0.044470	0.044470	0.628	0.0708	0.0708	34.92	34.92	47.50	47.50	12.58	12.58

Shape: Oval
Size of Bed :
Bed Weight: 1Kg
Bed Overlap: 15'
Blade Inclination: 10'

Sl No	Δp in orifice (mmH2O		Δp Air (mH2O)		C_d	Orifice area, a_2 (m2)	d/D	Flow (m3/sec)		Bed area in (m2)	u (m/sec)		Distributor Δp (mmH2O)		Distributor Δp + Bed Δp (mmH2O)		Bed Δp (mmH2O)	
	F	R	F	R				F	R		F	R	F	R	F	R	F	R
1	0	0	0.000	0.000	0.668	0.003018	0.620	0.000000	0.000000	0.628	0.0000	0.0000	0	0	0	0	0.00	0.00
2	0.14	0.17	0.117	0.142	0.668	0.003018	0.620	0.003303	0.003640	0.628	0.0053	0.0058	0.34	0.37	0.42	0.44	0.08	0.07
3	10.55	8.11	8.792	6.758	0.668	0.003018	0.620	0.028677	0.025143	0.628	0.0457	0.0400	2.54	2.59	13.22	10.08	10.68	7.49
4	19.77	18.34	16.475	15.283	0.668	0.003018	0.620	0.039257	0.037810	0.628	0.0625	0.0602	7.55	7.48	26.46	23.34	18.91	15.86
5	21.83	22.88	18.192	19.067	0.668	0.003018	0.620	0.041251	0.042231	0.628	0.0657	0.0672	13.64	14.02	33.17	32.07	19.53	18.05
6	22.32	23.14	18.600	19.283	0.668	0.003018	0.620	0.041711	0.042471	0.628	0.0664	0.0676	26.38	25.90	44.03	42.78	17.65	16.88
7	23.30	23.61	19.417	19.675	0.668	0.003018	0.620	0.042617	0.042900	0.628	0.0679	0.0683	32.23	32.32	49.05	48.72	16.82	16.40
8	24.68	23.83	20.567	19.858	0.668	0.003018	0.620	0.043861	0.043099	0.628	0.0698	0.0686	34.98	35.05	51.05	51.18	16.07	16.13
9	25.44	25.02	21.200	20.850	0.668	0.003018	0.620	0.044531	0.044162	0.628	0.0709	0.0703	35.82	35.66	51.70	51.54	15.88	15.88
10	26.52	25.82	22.100	21.517	0.668	0.003018	0.620	0.045467	0.044863	0.628	0.0724	0.0714	35.34	35.51	51.38	51.05	16.04	15.54
11	27.62	27.62	23.017	23.017	0.668	0.003018	0.620	0.046400	0.046400	0.628	0.0739	0.0739	34.92	34.92	50.72	50.72	15.80	15.80

Sample Excel Sheet Calculations for Blade Overlap Angle of 18°

Cylindrical Particle

Shape: Cyclindrical
Size of Bed :
Bed Weight: 500g
Bed Overlap:18°
Blade Inclination: 10°

SI No	Δp in orifice (mmH2O)		Δp Air (mH2O)		C_d	Orifice area, a_2 (m2)	d/D	Flow (m3/sec)		Bed area in (m2)	u (m/sec)		Distributor Δp (mmH2O)		Distributor Δp + Bed Δp (mmH2O)		Bed Δp (mmH2O)	
	F	R	F	R				F	R		F	R	F	R	F	R	F	R
1	0.00	0.00	0.00	0.00	0.668	0.003018	0.620	0.000000	0.000000	0.628	0.0000	0.0000	0.00	0.00	0.00	0.00	0.00	0.00
2	0.07	0.20	0.06	0.17	0.668	0.003018	0.620	0.002336	0.003948	0.628	0.0037	0.0063	0.29	0.29	0.29	0.32	0.00	0.03
3	3.88	3.73	3.23	3.11	0.668	0.003018	0.620	0.017391	0.017052	0.628	0.0277	0.0272	3.04	2.75	18.24	4.38	15.20	1.63
4	9.19	9.25	7.66	7.71	0.668	0.003018	0.620	0.026765	0.026852	0.628	0.0426	0.0428	7.65	7.62	24.03	10.53	16.38	2.91
5	14.79	17.03	12.33	14.19	0.668	0.003018	0.620	0.033954	0.036435	0.628	0.0541	0.0580	14.45	14.37	30.37	19.33	15.92	4.96
6	21.54	20.50	17.95	17.08	0.668	0.003018	0.620	0.040976	0.039975	0.628	0.0652	0.0637	26.79	26.97	35.77	34.80	8.98	7.83
7	25.84	22.46	21.53	18.72	0.668	0.003018	0.620	0.044880	0.041842	0.628	0.0715	0.0666	33.38	33.34	41.38	41.83	8.00	8.49
8	27.25	23.33	22.71	19.44	0.668	0.003018	0.620	0.046088	0.042645	0.628	0.0734	0.0679	36.28	36.04	44.30	44.73	8.02	8.69
9	28.13	23.66	23.44	19.72	0.668	0.003018	0.620	0.046827	0.042945	0.628	0.0746	0.0684	36.59	36.66	45.37	45.59	8.78	8.93
10	28.35	24.24	23.63	20.20	0.668	0.003018	0.620	0.047009	0.043468	0.628	0.0749	0.0692	36.32	36.60	45.50	45.04	9.18	8.44
11	29.05	29.05	24.21	24.21	0.668	0.003018	0.620	0.047586	0.047586	0.628	0.0758	0.0758	35.96	35.96	44.61	44.61	8.65	8.65

Shape: Cyclindrical
Size of Bed :
Bed Weight: 750g
Bed Overlap:18°
Blade Inclination: 10°

SI No	Δp in orifice (mmH2O)		Δp Air (mH2O)		C_d	Orifice area, a_2 (m2)	d/D	Flow (m3/sec)		Bed area in (m2)	u (m/sec)		Distributor Δp (mmH2O)		Distributor Δp + Bed Δp (mmH2O)		Bed Δp (mmH2O)	
	F	R	F	R				F	R		F	R	F	R	F	R	F	R
1	0.00	0.00	0.00	0.00	0.668	0.003018	0.620	0.000000	0.000000	0.628	0.0000	0.0000	0.00	0.00	0.00	0.00	0.00	0.00
2	0.08	0.12	0.07	0.10	0.668	0.003018	0.620	0.002497	0.003058	0.628	0.0040	0.0049	0.29	0.29	0.35	0.36	0.06	0.07
3	9.99	5.83	8.33	4.86	0.668	0.003018	0.620	0.027906	0.021318	0.628	0.0444	0.0339	3.04	2.75	10.54	6.55	7.50	3.80
4	18.99	14.11	15.83	11.76	0.668	0.003018	0.620	0.038474	0.033164	0.628	0.0613	0.0528	7.65	7.62	19.88	15.45	12.23	7.83
5	26.48	24.65	22.07	20.54	0.668	0.003018	0.620	0.045433	0.043835	0.628	0.0723	0.0698	14.45	14.37	29.55	27.55	15.10	13.18
6	33.18	33.58	27.65	27.98	0.668	0.003018	0.620	0.050856	0.051162	0.628	0.0810	0.0815	26.79	26.97	39.56	39.88	12.77	12.91
7	38.17	38.49	31.81	32.08	0.668	0.003018	0.620	0.054547	0.054775	0.628	0.0869	0.0872	33.38	33.34	45.56	45.05	12.18	11.71
8	39.76	39.77	33.13	33.14	0.668	0.003018	0.620	0.055671	0.055678	0.628	0.0886	0.0887	36.28	36.04	47.77	47.70	11.49	11.66
9	40.24	40.48	33.53	33.73	0.668	0.003018	0.620	0.056006	0.056173	0.628	0.0892	0.0894	36.59	36.66	49.09	48.81	12.50	12.15
10	40.58	40.83	33.82	34.03	0.668	0.003018	0.620	0.056242	0.056415	0.628	0.0896	0.0898	36.32	36.60	47.87	48.10	11.55	11.50
11	41.36	41.36	34.47	34.47	0.668	0.003018	0.620	0.056780	0.056780	0.628	0.0904	0.0904	35.96	35.96	47.61	47.61	11.65	11.65

Shape: Cyclindrical
Size of Bed :
Bed Weight: 1Kg
Bed Overlap:18°
Blade Inclization: 10°

SI No	Δp in orifice (mmH2O)		Δp Air (mH2O)		C_d	Orifice area, a_2 (m2)	d/D	Flow (m3/sec)		Bed area in (m2)	u (m/sec)		Distributor Δp (mmH2O)		Distributor Δp + Bed Δp (mmH2O)		Bed Δp (mmH2O)	
	F	R	F	R				F	R		F	R	F	R	F	R	F	R
1	0.00	0.00	0.00	0.00	0.668	0.003018	0.620	0.000000	0.000000	0.628	0.0000	0.0000	0.00	0.00	0.00	0.00	0.00	0.00
2	0.13	0.14	0.11	0.12	0.668	0.003018	0.620	0.003183	0.003303	0.628	0.0051	0.0053	0.29	0.29	0.30	0.33	0.01	0.04
3	8.03	5.92	6.69	4.93	0.668	0.003018	0.620	0.025019	0.021482	0.628	0.0398	0.0342	3.04	2.75	8.71	6.65	5.67	3.90
4	18.75	13.82	15.63	11.52	0.668	0.003018	0.620	0.038230	0.032822	0.628	0.0609	0.0523	7.65	7.62	20.12	15.37	12.47	7.75
5	30.54	23.58	25.45	19.65	0.668	0.003018	0.620	0.048791	0.042873	0.628	0.0777	0.0683	14.45	14.37	32.79	26.26	18.34	11.89
6	38.73	39.86	32.28	33.22	0.668	0.003018	0.620	0.054945	0.055741	0.628	0.0875	0.0888	26.79	26.97	44.34	45.38	17.55	18.41
7	42.76	43.03	35.63	35.86	0.668	0.003018	0.620	0.057733	0.057915	0.628	0.0919	0.0922	33.38	33.34	49.83	49.28	16.45	15.94
8	44.29	44.55	36.91	37.13	0.668	0.003018	0.620	0.058757	0.058929	0.628	0.0936	0.0938	36.28	36.04	52.09	52.43	15.81	16.39
9	44.88	44.87	37.40	37.39	0.668	0.003018	0.620	0.059147	0.059141	0.628	0.0942	0.0942	36.59	36.66	52.82	53.54	16.23	16.88
10	45.05	45.02	37.54	37.52	0.668	0.003018	0.620	0.059259	0.059239	0.628	0.0944	0.0943	36.32	36.60	52.35	52.87	16.03	16.27
11	45.55	45.55	37.96	37.96	0.668	0.003018	0.620	0.059587	0.059587	0.628	0.0949	0.0949	35.96	35.96	51.99	51.99	16.03	16.03

Spherical Particle

Shape: Spherical
Size of Bed :
Bed Weight: 500g
Bed Overlap:18°
Blade Inclination: 10°

Sl No	Δp in orifice (mmH2O)		Δp Air (mH2O)		C_d	Orifice area, a_2 (m2)	d/D	Flow (m3/sec)		Bed area in (m2)	u (m/sec)		Distributor Δp (mmH2O)		Distributor Δp + Bed Δp (mmH2O)		Bed Δp (mmH2O)	
	F	R	F	R				F	R		F	R	F	R	F	R	F	R
1	0.00	0.00	0.000	0.000	0.668	0.003018	0.620	0.000000	0.000000	0.628	0.0000	0.0000	0.00	0.00	0.00	0.00	0.00	0.00
2	0.08	0.42	0.067	0.350	0.668	0.003018	0.620	0.002497	0.005722	0.628	0.0040	0.0091	0.29	0.29	0.37	1.02	0.08	0.73
3	6.34	7.88	5.283	6.567	0.668	0.003018	0.620	0.022231	0.024784	0.628	0.0354	0.0395	3.04	2.75	8.13	10.55	5.09	7.80
4	10.26	11.45	8.550	9.542	0.668	0.003018	0.620	0.028280	0.029875	0.628	0.0450	0.0476	7.65	7.62	14.69	16.43	7.04	8.81
5	13.27	13.22	11.058	11.017	0.668	0.003018	0.620	0.032162	0.032101	0.628	0.0512	0.0511	14.45	14.37	23.32	24.82	8.87	10.45
6	16.76	14.36	13.967	11.967	0.668	0.003018	0.620	0.036145	0.033457	0.628	0.0576	0.0533	26.79	26.97	35.13	35.49	8.34	8.52
7	17.33	14.39	14.442	11.992	0.668	0.003018	0.620	0.036754	0.033492	0.628	0.0585	0.0533	33.38	33.34	41.25	41.24	7.87	7.90
8	17.77	14.99	14.808	12.492	0.668	0.003018	0.620	0.037218	0.034183	0.628	0.0593	0.0544	36.28	36.04	43.52	43.85	7.24	7.81
9	18.19	15.11	15.158	12.592	0.668	0.003018	0.620	0.037655	0.034319	0.628	0.0600	0.0546	36.59	36.66	44.02	44.27	7.43	7.61
10	18.74	19.06	15.617	15.883	0.668	0.003018	0.620	0.038220	0.038545	0.628	0.0609	0.0614	36.32	36.60	43.81	43.73	7.49	7.13
11	19.20	19.20	16.000	16.000	0.668	0.003018	0.620	0.038686	0.038686	0.628	0.0616	0.0616	35.96	35.96	43.45	43.45	7.49	7.49

Shape: Spherical
Size of Bed :
Bed Weight: 750g
Bed Overlap:18°
Blade Inclination: 10°

Sl No	Δp in orifice (mmH2O)		Δp Air (mH2O)		C_d	Orifice area, a_2 (m2)	d/D	Flow (m3/sec)		Bed area in (m2)	u (m/sec)		Distributor Δp (mmH2O)		Distributor Δp + Bed Δp (mmH2O)		Bed Δp (mmH2O)	
	F	R	F	R				F	R		F	R	F	R	F	R	F	R
1	0.00	0.00	0.00	0.00	0.668	0.003018	0.620	0.000000	0.000000	0.628	0.0000	0.0000	0.00	0.00	0.00	0.00	0.00	0.00
2	0.37	0.13	0.31	0.11	0.668	0.003018	0.620	0.005370	0.003183	0.628	0.0086	0.0051	0.29	0.29	0.88	0.48	0.59	0.19
3	14.17	10.74	11.81	8.95	0.668	0.003018	0.620	0.033235	0.028934	0.628	0.0529	0.0461	3.04	2.75	17.55	13.19	14.51	10.44
4	15.94	16.90	13.28	14.08	0.668	0.003018	0.620	0.035249	0.036295	0.628	0.0561	0.0578	7.65	7.62	21.00	21.25	13.35	13.63
5	18.45	19.28	15.38	16.07	0.668	0.003018	0.620	0.037923	0.038767	0.628	0.0604	0.0617	14.45	14.37	29.32	29.55	14.87	15.18
6	22.27	20.84	18.56	17.37	0.668	0.003018	0.620	0.041665	0.040305	0.628	0.0663	0.0642	26.79	26.97	38.37	40.33	11.58	13.36
7	22.44	21.39	18.70	17.83	0.668	0.003018	0.620	0.041823	0.040833	0.628	0.0666	0.0650	33.38	33.34	45.51	45.87	12.13	12.53
8	22.82	21.69	19.02	18.08	0.668	0.003018	0.620	0.042176	0.041119	0.628	0.0672	0.0655	36.28	36.04	47.62	48.06	11.34	12.02
9	23.42	22.05	19.52	18.38	0.668	0.003018	0.620	0.042727	0.041458	0.628	0.0680	0.0660	36.59	36.66	48.47	48.36	11.88	11.70
10	25.75	24.49	21.46	20.41	0.668	0.003018	0.620	0.044802	0.043692	0.628	0.0713	0.0696	36.32	36.60	48.07	48.12	11.75	11.52
11	26.10	26.10	21.75	21.75	0.668	0.003018	0.620	0.045105	0.045105	0.628	0.0718	0.0718	35.96	35.96	47.56	47.56	11.60	11.60

Shape: Spherical
Size of Bed :
Bed Weight: 1Kg
Bed Overlap:18°
Blade Inclination: 10°

Sl No	Δp in orifice (mmH2O)		Δp Air (mH2O)		C_d	Orifice area, a_2 (m2)	d/D	Flow (m3/sec)		Bed area in (m2)	u (m/sec)		Distributor Δp (mmH2O)		Distributor Δp + Bed Δp (mmH2O)		Bed Δp (mmH2O)	
	F	R	F	R				F	R		F	R	F	R	F	R	F	R
1	0.00	0.00	0.00	0.00	0.668	0.003018	0.620	0.000000	0.000000	0.628	0.0000	0.0000	0.00	0.00	0.00	0.00	0.00	0.00
2	0.05	0.09	0.04	0.08	0.668	0.003018	0.620	0.001974	0.002649	0.628	0.0031	0.0042	0.29	0.29	0.58	0.54	0.29	0.25
3	16.19	9.92	13.49	8.27	0.668	0.003018	0.620	0.035525	0.027808	0.628	0.0566	0.0443	3.04	2.75	20.99	12.23	17.95	9.48
4	21.24	18.66	17.70	15.55	0.668	0.003018	0.620	0.040690	0.038139	0.628	0.0648	0.0607	7.65	7.62	29.30	25.19	21.65	17.57
5	21.48	22.69	17.90	18.91	0.668	0.003018	0.620	0.040919	0.042056	0.628	0.0652	0.0670	14.45	14.37	33.12	34.22	18.67	19.85
6	22.84	23.95	19.03	19.96	0.668	0.003018	0.620	0.042195	0.043208	0.628	0.0672	0.0688	26.79	26.97	45.00	44.24	18.21	17.27
7	23.42	24.72	19.52	20.60	0.668	0.003018	0.620	0.042727	0.043897	0.628	0.0680	0.0699	33.38	33.34	50.04	50.26	16.66	16.92
8	24.07	25.42	20.06	21.18	0.668	0.003018	0.620	0.043316	0.044514	0.628	0.0690	0.0709	36.28	36.04	52.66	52.62	16.38	16.58
9	27.43	27.62	22.86	23.02	0.668	0.003018	0.620	0.046240	0.046400	0.628	0.0736	0.0739	36.59	36.66	53.27	53.18	16.68	16.52
10	27.76	29.69	23.13	24.74	0.668	0.003018	0.620	0.046518	0.048108	0.628	0.0741	0.0766	36.32	36.60	52.92	53.04	16.60	16.44
11	31.85	31.80	26.54	26.50	0.668	0.003018	0.620	0.049827	0.049788	0.628	0.0793	0.0793	35.96	35.96	52.54	52.54	16.58	16.58

Oval Particle

Shape: Spherical
Size of Bed :
Bed Weight: 500g
Bed Overlap:18°
Blade Inclination: 10°

Sl No	∆p in orifice (mmH2O)		∆p Air (mH2O)		C_d	Orifice area, a_2 (m2)	d/D	Flow (m3/sec)		Bed area in (m2)	u (m/sec)		Distributor ∆p (mmH2O)		Distributor ∆p + Bed ∆p (mmH2O)		Bed ∆p (mmH2O)	
	F	R	F	R				F	R		F	R	F	R	F	R	F	R
1	0.00	0.00	0.00	0.00	0.668	0.003018	0.620	0.000000	0.000000	0.628	0.0000	0.0000	0.00	0.00	0.00	0.00	0.00	0.00
2	0.08	0.15	0.07	0.13	0.668	0.003018	0.620	0.002497	0.003419	0.628	0.0040	0.0054	0.29	0.29	0.29	0.32	0.00	0.03
3	7.86	5.96	6.55	4.97	0.668	0.003018	0.620	0.024753	0.021554	0.628	0.0394	0.0343	3.04	2.75	10.24	7.75	7.20	5.00
4	12.12	12.35	10.10	10.29	0.668	0.003018	0.620	0.030737	0.031027	0.628	0.0489	0.0494	7.65	7.62	17.75	16.68	10.10	9.06
5	14.44	15.55	12.03	12.96	0.668	0.003018	0.620	0.033550	0.034816	0.628	0.0534	0.0554	14.45	14.37	24.60	23.62	10.15	9.25
6	17.44	15.98	14.53	13.32	0.668	0.003018	0.620	0.036871	0.035294	0.628	0.0587	0.0562	26.79	26.97	36.11	35.84	9.32	8.87
7	20.06	16.25	16.72	13.54	0.668	0.003018	0.620	0.039543	0.035591	0.628	0.0630	0.0567	33.38	33.34	42.08	42.23	8.70	8.89
8	22.13	17.10	18.44	14.25	0.668	0.003018	0.620	0.041534	0.036510	0.628	0.0661	0.0581	36.28	36.04	44.40	44.76	8.12	8.72
9	22.41	20.20	18.68	16.83	0.668	0.003018	0.620	0.041795	0.039681	0.628	0.0666	0.0632	36.59	36.66	45.59	45.65	9.00	8.99
10	23.10	23.90	19.25	19.92	0.668	0.003018	0.620	0.042434	0.043163	0.628	0.0676	0.0687	36.32	36.60	45.01	45.15	8.69	8.55
11	24.58	24.58	20.48	20.48	0.668	0.003018	0.620	0.043772	0.043772	0.628	0.0697	0.0697	35.96	35.96	44.95	44.95	8.99	8.99

Shape: oval
Size of Bed :
Bed Weight: 750g
Bed Overlap:18°
Blade Inclination: 10°

Sl No	∆p in orifice (mmH2O)		∆p Air (mH2O)		C_d	Orifice area, a_2 (m2)	d/D	Flow (m3/sec)		Bed area in (m2)	u (m/sec)		Distributor ∆p (mmH2O)		Distributor ∆p + Bed ∆p (mmH2O)		Bed ∆p (mmH2O)	
	F	R	F	R				F	R		F	R	F	R	F	R	F	R
1	0.00	0.00	0.00	0.00	0.668	0.003018	0.620	0.000000	0.000000	0.628	0.0000	0.0000	0.00	0.00	0.00	0.00	0.00	0.00
2	0.09	0.12	0.08	0.10	0.668	0.003018	0.620	0.002649	0.003058	0.628	0.0042	0.0049	0.29	0.29	0.33	0.44	0.04	0.15
3	9.85	7.05	8.21	5.88	0.668	0.003018	0.620	0.027709	0.023442	0.628	0.0441	0.0373	3.04	2.75	12.71	8.97	9.67	6.22
4	15.55	16.15	12.96	13.46	0.668	0.003018	0.620	0.034816	0.035481	0.628	0.0554	0.0565	7.65	7.62	22.27	20.50	14.62	12.88
5	19.38	19.80	16.15	16.50	0.668	0.003018	0.620	0.038867	0.039286	0.628	0.0619	0.0626	14.45	14.37	28.56	28.27	14.11	13.90
6	22.35	23.70	18.63	19.75	0.668	0.003018	0.620	0.041739	0.042982	0.628	0.0665	0.0684	26.79	26.97	39.87	38.80	13.08	11.83
7	23.75	24.85	19.79	20.71	0.668	0.003018	0.620	0.043027	0.044012	0.628	0.0685	0.0701	33.38	33.34	45.75	45.28	12.37	11.94
8	24.94	25.35	20.78	21.13	0.668	0.003018	0.620	0.044092	0.044453	0.628	0.0702	0.0708	36.28	36.04	48.37	48.10	12.09	12.06
9	25.61	26.42	21.34	22.02	0.668	0.003018	0.620	0.044680	0.045381	0.628	0.0711	0.0723	36.59	36.66	48.79	48.78	12.20	12.12
10	27.55	27.14	22.96	22.62	0.668	0.003018	0.620	0.046341	0.045995	0.628	0.0738	0.0732	36.32	36.60	48.16	48.42	11.84	11.82
11	28.87	28.87	24.06	24.06	0.668	0.003018	0.620	0.047439	0.047439	0.628	0.0755	0.0755	35.96	35.96	48.02	48.02	12.06	12.06

Shape: Oval
Size of Bed :
Bed Weight: 1Kg
Bed Overlap:18°
Blade Inclination: 10°

Sl No	∆p in orifice (mmH2O		∆p Air (mH2O)		C_d	Orifice area, a_2 (m2)	d/D	Flow (m3/sec)		Bed area in (m2)	u (m/sec)		Distributor ∆p (mmH2O)		Distributor ∆p + Bed ∆p (mmH2O)		Bed ∆p (mmH2O)	
	F	R	F	R				F	R		F	R	F	R	F	R	F	R
1	0.00	0.00	0.00	0.00	0.668	0.003018	0.620	0.000000	0.000000	0.628	0.0000	0.0000	0.00	0.00	0.00	0.00	0.00	0.00
2	0.05	0.19	0.04	0.16	0.668	0.003018	0.620	0.001974	0.003848	0.628	0.0031	0.0061	0.29	0.29	0.46	0.42	0.17	0.13
3	9.92	8.92	8.27	7.43	0.668	0.003018	0.620	0.027808	0.026369	0.628	0.0443	0.0420	3.04	2.75	12.15	11.11	9.11	8.36
4	19.76	18.24	16.47	15.20	0.668	0.003018	0.620	0.039247	0.037707	0.628	0.0625	0.0600	7.65	7.62	26.16	23.70	18.51	16.08
5	22.26	22.38	18.55	18.65	0.668	0.003018	0.620	0.041655	0.041767	0.628	0.0663	0.0665	14.45	14.37	33.43	32.25	18.98	17.88
6	23.31	24.14	19.43	20.12	0.668	0.003018	0.620	0.042626	0.043379	0.628	0.0679	0.0691	26.79	26.97	43.22	43.09	16.43	16.12
7	24.94	24.68	20.78	20.57	0.668	0.003018	0.620	0.044092	0.043861	0.628	0.0702	0.0698	33.38	33.34	48.90	48.69	15.52	15.35
8	25.35	25.55	21.13	21.29	0.668	0.003018	0.620	0.044453	0.044628	0.628	0.0708	0.0711	36.28	36.04	51.23	51.18	14.95	15.14
9	26.48	26.97	22.07	22.48	0.668	0.003018	0.620	0.045433	0.045851	0.628	0.0723	0.0730	36.59	36.66	51.78	51.77	15.19	15.11
10	26.81	27.13	22.34	22.61	0.668	0.003018	0.620	0.045715	0.045987	0.628	0.0728	0.0732	36.32	36.60	51.58	51.25	15.26	14.65
11	28.50	28.50	23.75	23.75	0.668	0.003018	0.620	0.047134	0.047134	0.628	0.0751	0.0751	35.96	35.96	51.12	51.12	15.16	15.16