CHAPTER 1
INTRODUCTION

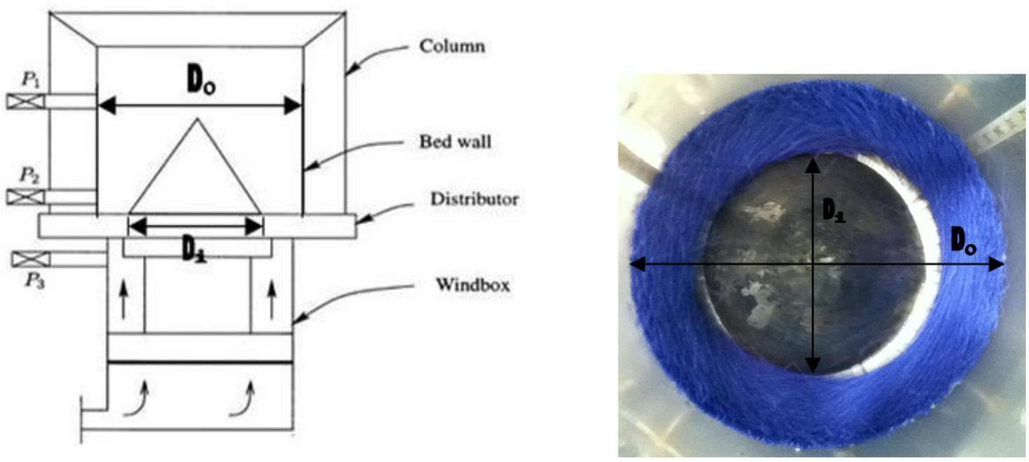
1.1 Background of Study

Fluidization is a process where solid particles behave like fluid, mixing with other particles and flows like liquid or gas. This will result in intense contact between solid and fluid [1]. Through the years, the fluidization method has been used extensively in many industrial areas that require intense contact between solids and fluids in its process, i.e. fluidized bed reactors, fluid catalytic cracking, fluidized bed combustion and heat or mass transfer process or surface coating [2].

Swirling fluidized bed (SFB) is a development in the field of fluidization [2]. Swirling fluidized bed is also known as toroidal bed, as proposed by [3,4]. In swirling fluidization, momentum is transferred radially and tangentially to the bed particles, thereby increasing the fluidization quality and reducing the particle elutriation. The rate of heat and mass transfer to and from the bed rapidly increases as the solid particles and liquid mixing vigorously [4].

Faizal et al. [2] proved that SFB is superior compared to conventional fluidized bed. The potential energy required by SFB for fluidization is only half of that required by conventional fluidized bed. The minimum fluidization velocity in SFB is also much lower. Therefore, better fluidization results can be expected when SFB is used in processes which require solid-fluid interaction.

The current work focuses on swirling fluidization using an annular distributor with modified blades. In spite of the potential for vast industrial applications, the SFB has an inherent tendency of maldistribution of the gas at the exit of the distributor. This will cause accumulation of the solid particles at the outer periphery of the bed by virtue of the centrifugal action resulting in the restriction of the annular bed width. In other words, the ratio of inner diameter to outer diameter, D_i / D_o, is limited to values higher than 0.7, refer to Figure 1.1 [5]. This seriously limits the utilization of the Swirling Bed, especially during scaling up to industrial sizes.



(a) (b)

Figure 1.1(a)-(b) Inner Diameter (D_i) and Outer Diameter (D_o) Illustration of Annular Distributor

Prof. Vijay Raghavan [5] proposed one solution to lower the gas velocity at inner radius. By doing this, the swirling speeds from the inner to the outer periphery blades will vary. In order to achieve this, it is proposed to have distributor with blades continuously twisted in the radial direction, somewhat like high pressure axial compressors blades, distributor with twisted blades will be installed on the pre-existing SFB apparatus.

1.2 Problem Statement

(i) The maldistribution of the flow profile of current distributor limits the industrial scale up for SFB.

(ii) Low utilization area efficiency of SFB. The current distributor configuration shows that swirling only happen at the outer periphery, utilizing only around 30% of the available area.

1.3 Objective

The modified profile of blades distributor is expected to increase the utilized area of SFB. The project objectives are:

(i) To modify the distributor blade profile in SFB

(ii) To investigate the effect of longer and continuously twisted distributor blades on the SFB

1.4 Scope of Study

(i) The project is limited to design, fabricate, and test distributor with twisted profile blades.

(ii) Experiments will be conducted in order to study the hydrodynamics of the bed as in the flow regimes, bed pressure drop and superficial velocity.

(iii) Experiments will also be conducted to determine the effectiveness of the available annular area increment.

CHAPTER 2

LITERATURE REVIEW

2.1 Fludization and Swirling Fluidized Bed Overview

Swirling Fluidized Bed (SFB) utilizes annular distributor with an annular bed and inclined injection of gas through the distributor and this setup will result in swirling motion of the particles inside the bed. It was first studied analytically by Sreenivasan and Raghavan [3]. According to Sreenivasan and Raghavan [3], the gas entering the bed will have horizontal and vertical components. The vertical component results in fluidization while the horizontal component results in swirling motion of the particles.

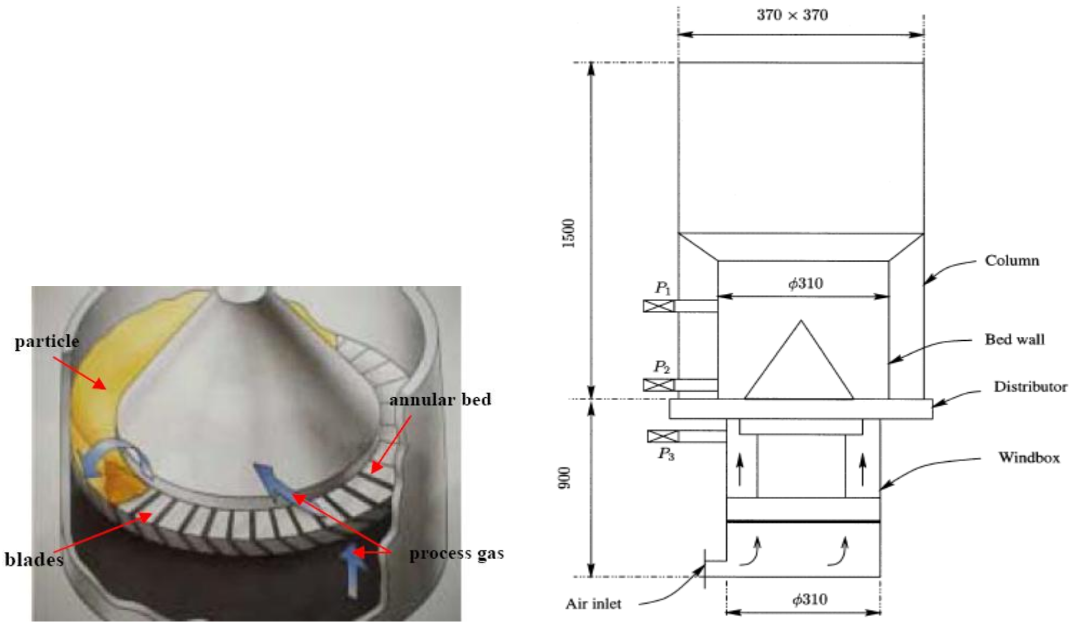


Figure 2.1 Basic Configuration of SFB by Sreenivasan and Raghavan (all dimensions in mm) [Reproduced from 3, p.32]

Vikram et al.[4] also reported that the distributor blade inclination angle and overlapping angle has significant influence on the bed hydrodynamic characteristic, i.e. bed pressure drop and also swirl velocity. Further to this statement, Sreenivasan and Raghavan [3] found out that blade inclination angle is factor that affects the swirl characteristic the most, compared to other parameters like particle type & size, bed weight, and inclination angle . Sreenivasan and Raghavan [3] also stated that only a small portion of available area of SFB is useful. To overcome this, they proposed one solution which consists of having lower gas velocities at the inner radius. As a result, the swirling speeds from the inner to the outer periphery blades will vary.

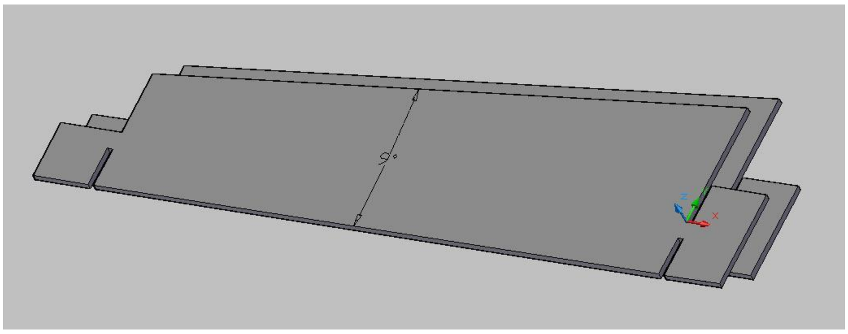


Figure 2.2 Illustration of Blades Overlapping Angle (9^o)

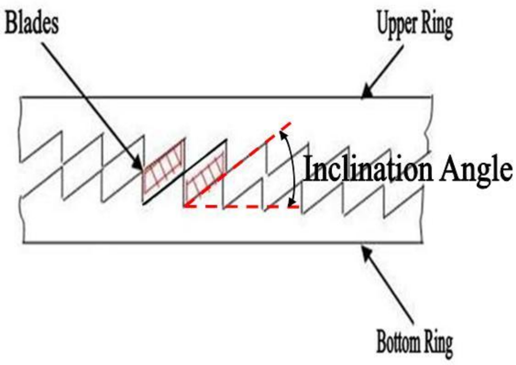


Figure 2.3 Illustration of Blades Inclination Angle

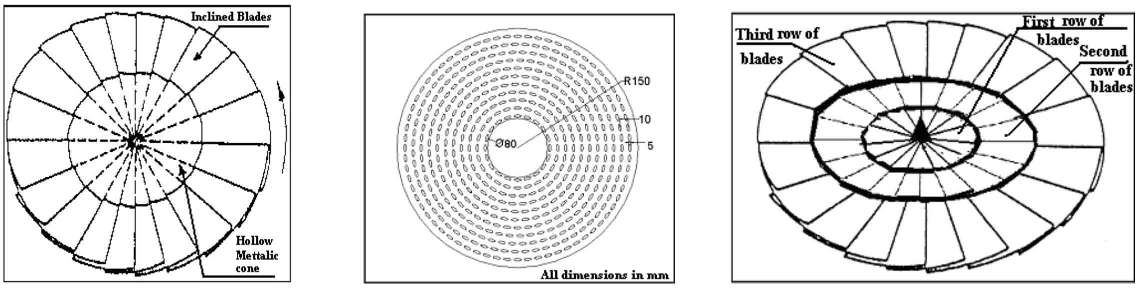
2.2 Other Study on Annular Area Extension for SFB

There were a few studies carried out in the past to increase the annular area utilization for SFB. One is by utilizing different distributor types, while the other is using a multiple fluid inlets. The details of the experiments are explained as follows:

2.2.1 Different Types of Distributor

Kumar et al. [8] proposed three distributor types: (i) inclined blades in a single row, (ii) perforated plate with inclined holes and (iii) inclined blades in three rows. For these blades, the working fluid (air) was injected to the bed at an angle of 15^o.

The single row distributor is fabricated by installing 60 mild steel blades in a slotted Perspex ring, as shown by Figure 2.2 (a). This configuration provides a trapezoidal opening area in between the blades. The opening area was measured at 5105 mm^2, $\pm$ 1% of the total area of the distributor. The second distributor (perforated plate with inclined holes) was made by drilling a 25 mm-thickness Perspex. All the inclined holes were on a circular pitch as shown in fig. 3 (b). A total of 502 holes were drilled with inner diameter of 5 mm. The opening area provided is 9818 mm^2, occupying $\pm$ 10% of the distributor area. The third distributor is the three rows type. The material used for this distributor was mild steel. As shown in Figure 2.2 (c), there are 60 blades at the outer row, 45 blades in the middle row, and 30 blades in the inner row. The total trapezoidal opening was 5692.5 mm^2, works out to about 15 % of the distributor area.



(a) (b) (c)

Figure 2.4 Distributors Used by Kumar et al. (a) Single Row Inclined Bed; (b) Perforated Plates and Inclined Holes; (c) Triple Row Inclined Bed [Reproduced from 8, p.32]

Kumar et al. [8] concluded that the inclined-blade three-row type distributor is superior to both inclined-blade single-row type and the perforated plate. The perforated plate with inclined hole type distributor had very high distributor pressure drop compared to the other two distributors. Even though the result seems promising for distributor with triple rows, there was no further study on the area utilization efficiency for three rows distributor. But the author did state that the effective bed cross sectional area utilized in the inclined-blade single-row type distributor was less than the triple rows distributor, anyway the pressure drop reading shows that it is slightly higher than the distributor with single row due to the blade holders in between the rows. [8]

2.2.2 Distributor with Multiple Fluid Inlets

Kumar and Murthy in their publication [9] reported their study on the hydrodynamic behavior of swirled fluidized bed. In their study, tangentially located multiple fluid inlets at the base of a flat-bottom circular column were used to achieve the swirl flow. The swirl flow will occupy 100% of the circular area of the bed. The work did not give any details of the distributor that they have used. If there were no distributor, it would mean that there would be high agitation of particles than swirling because of different streams of air meeting inside the chamber. Even with a distributor, the swirling motion cannot be sustained to a deeper bed height as compared to SFB.

(a) (b)

Figure 2.5 Typical Column Base Assembly Bed With Multiple Fluid Inlets by Kumar and Murthy (A) Three Inlets; (B) Four Inlets [Reproduced from 9, P.32]

2.3 Engineering Design Process

According to Dieter and Smith [10], design is considered as a process of transforming apparent requirements into a product or collection of products to suit those requirements. Models of the design process can be differentiated as descriptive or prescriptive, and involves both analysis and synthesis. According to Dieter and Smith [10], the design process will follow the steps below:

Figure 2.6. Design Process [Reproduced from 10, P.32]

1. Define Problem: A clear and concise problem statement must be produced from the given problems. In this stage, a benchmark must be chosen to be the datum of the design. The benchmarking process will identify the best practice in the field of design and use it as an object of comparison.
2. Concept Generation: A set of concepts are generated to answer previously defined problem. There are two methods to be used in concept generation :

   a. Creative method: This method intended to help stimulate creative thinking. It includes brainstorming, synectics, transformations, and counter-planning.
   b. Rational method: This technique encourages a systematic approach in generating a conceptual design. The examples are by using morphology chart and evaluation matrix.
3. Concept evaluation: The evaluation can be done by few techniques as per below:
   a. PUGH evaluation matrix: direct comparison with datum, uses (+), (-), and (S) scale.
   b. Weighted Score Matrix: using a weighted rank and rating score.
   c. Benchmarking: a comparative study against the pre-selected datum.
4. Configuration design: The processes that are included in this stage are the selection of the most suitable material and manufacturing process, modeling, and sizing.
5. Detail design: In this stage, a robust and detailed drawing is produced

2.4 A Study on the Fabrication Process

Fabrication as an industrial term refers to building metal structures by cutting, bending, and assembling [11]. There will be several fabrication processes involved in the present work, they are:

1. Cutting

   By definition, cutting is a process to reduce the length, area, or volume of a material into desired dimension. Cutting can be done via sawing, shearing, or chiseling, torching, and via CNC (Computer Numerical Controller) cutters (using a laser, torch, electric discharge, or water jet) [11]. The CNC cutting process will provide the most precise result and it is able to cut material into complicated shape. One of the most common CNC cutters is the Electric Discharge Machine (EDM) Wire Cutter.

   - EDM Wire Cutter

     Electric discharge machining (EDM) is a manufacturing process whereby a desired shape is obtained using electrical discharges (sparks). Material is removed from the work piece by a series of rapidly recurring current discharges between two electrodes, separated by a dielectric liquid and subjected to an electric voltage. When the distance between the two electrodes is reduced, the intensity of the electric field in the volume between the electrodes becomes greater than the strength of the dielectric which breaks, allowing current to flow between the two electrodes. As a result, material is removed from both the electrodes [11].

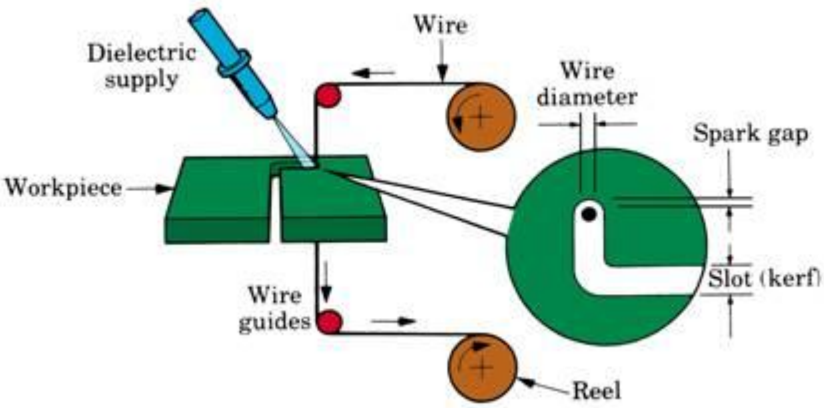


Figure 2.7 Schematic Edm Wire Cut Process [Reproduced from 12, p.32]

2. Twisting

   The process of twisting falls under the category of shaping. There are two possible methods to be used to produce the twist on the blades.

   a. Die Stamping

      Die stamping or progressive stamping is a method of metalworking that consists of punching, coining, bending, and several other ways to modify metal raw material combined with automatic feeding system. The die is placed into a reciprocating stamping press. When the press moves up, there will be an opening gap, thus material can be fed. As the press moves down, the die closes and the stamping operation is done. With each stroke of the press, the completed part is removed from the die [11].

   b. Manual Twisting

      This method is actually an idea generated by the author to produce a blade with a twisted profile. The principles are: the blade is clamped at both ends which will hold one end at static position and make the other end rotatable. When the rotatable clamp is turned, it will also turn the clamped end while the static end will stays at its original position. By this means, the blade profile will be twisted.

3. Sand Casting

   The process of sand casting does not require any cutting process. The selected material is first melted, and then it is poured into a pre-assembled mold, the molten metal is then subjected to cooling down. The final result is a complete distributor with blades. A final touch is required to achieve ideal finish of the product [11].

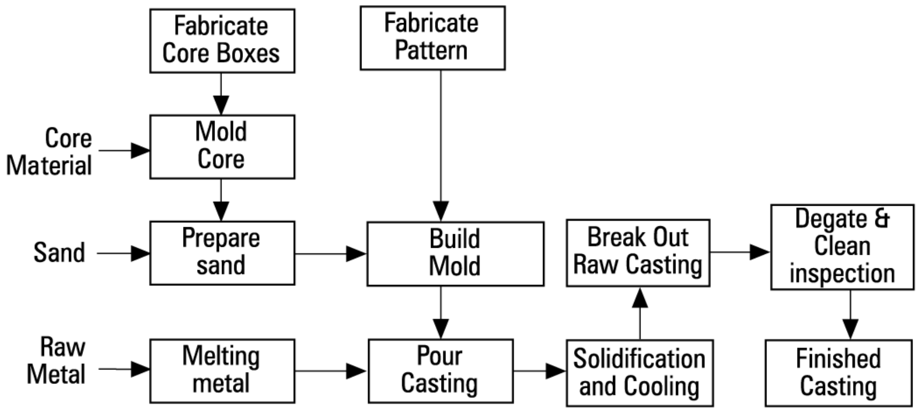


Figure 2.8 Sand Casting Process Flow [Reproduced from 11, p.32]

2.5 Hydrodynamic Regimes is Swirling Fluidized Bed

According to [2], the SFB operation for shallow bed (1000 g for instance) can be distinguished into several regimes. First will be the packed regime (regime I). When the fluidizing gas volumetric rate is increased and reaches the minimum fluidization level, the bed will start to behave in fluid-like manner. Further increase in fluidizing gas, will eventually start the particles to swirl gently and reached the minimum swirling condition (regime II). The desired swirling motion of the bed reached when the fluidizing gas flow rate progressively increased (regime III). This is the condition where both fluidization and swirling, where vigorous mixing occurs. The interaction between the particle and the gas are intense. This is the largest regime in which the particles will swirl faster with the increase of fluidizing gas rate and the increase of pressure drop. The final regime (regime IV) is the elutriation, where the particles are started to jump out of the bed for shallow bed.

In SFB, for heavier bed weight (1500 g) as observed by [2, 3] there are two layers of bed presents. The bottom of the bed is continuously swirling while the top layer is vigorously bubbling. This is due to the attenuation of the horizontal component of the superficial velocity. As a result of continuous momentum transfer inside the bed, the horizontal component will finally vanish at the boundary between two layers.

CHAPTER 3

METHODOLOGY

3.1 Design Phase

The design flow process is as follows:

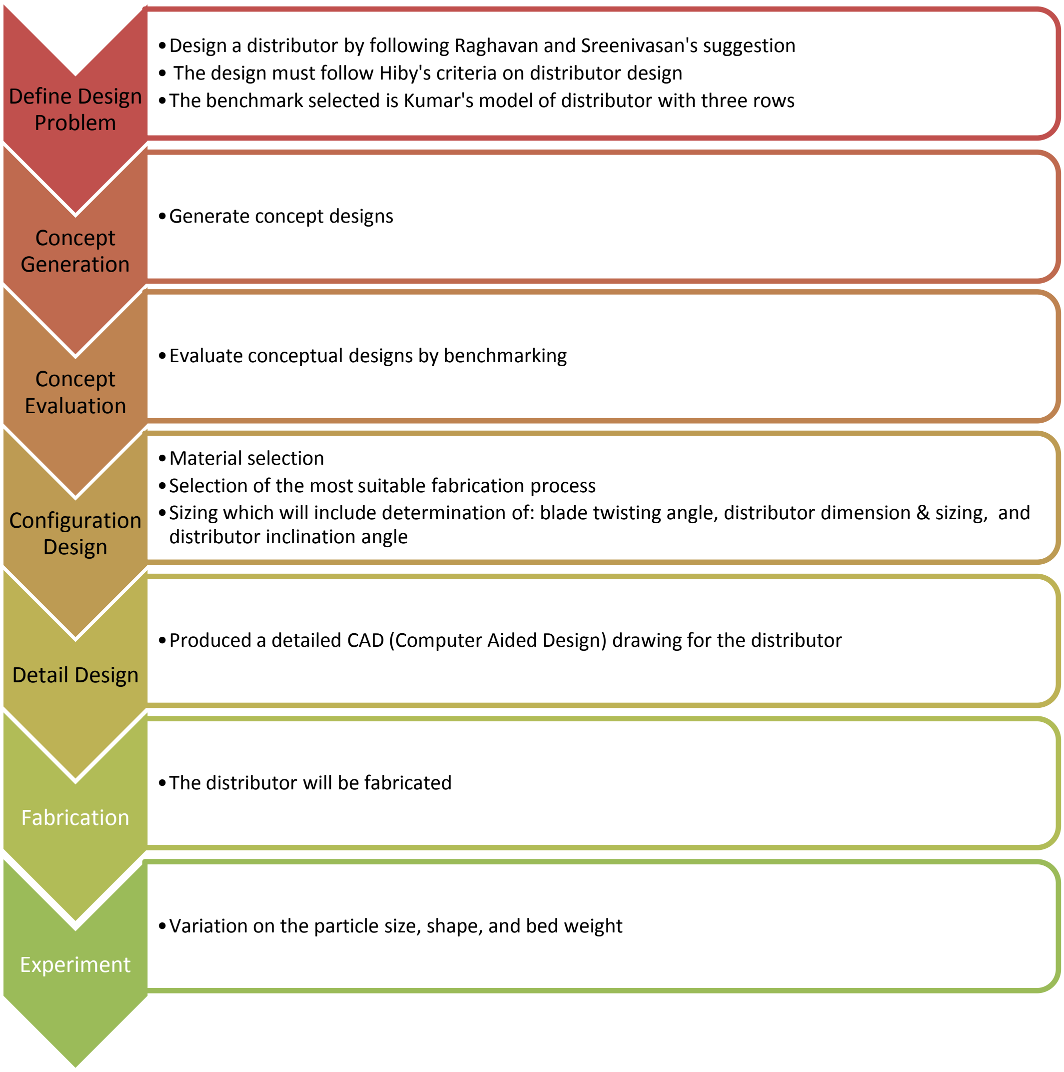


Figure 3.1. Steps in Project Methodology

3.2 Fabrication Phase

1. The new distributors are fabricated.
2. New distributors are assembled on the existing fluidized bed apparatus.

3.3 Experiment Phase

1. The equipment needed :

   Existing SFB Setup

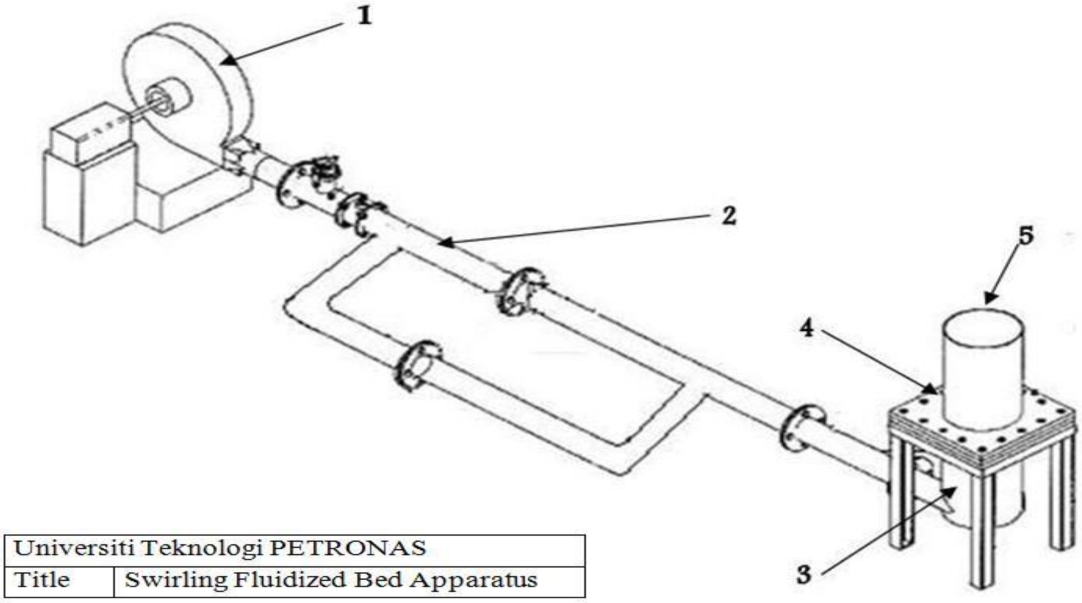


Figure 3.2. SFB Apparatus Setup [Reproduce from 3, p.24]

Table 1. Major Equipments for Experiment

Blower (1)	**Pipes (2)**	**Plenum Chamber (3)**
Brand: Massive Fan Group	Material: PVC	Material : Mild Steel
CFM: 1000 cmh	Inner Diameter: 100 mm	Height : 1100 mm
5.5 kW	Outer Diameter: 115 mm	Inner Diameter : 300 mm
7.5 HP	Length: straight - 5000 mm n junction - 600 mm + 3200 mm + 600 mm	Depth : 490 mm
Column Flange (4)	**Bed Column (5)**	**Piezometric Ring (inside 5)**
Material : Perspex	Material : Perspex	Will be installed in the plenum chamber and in the bed column. The function is to measure the pressure at the chamber and the column.
Size : 425 mm x 425 mm	Height : 600 mm	Material : Hose and Metal Pluck
Thickness : 20 mm	ID : 300 mm OD : 310 mm	Hose diameter : 5 mm

2. Run the experiment by varying a few parameters as follows :

   - Bed Weight - weight used are 1000 g, 1500 g, and 2000 g
   - Particles Size and Shape - particles used are big sphere, small sphere, irregular-flat particles, and irregular-rice particle.
   - The controlled parameter is the pressure flow from the blower which measured using choke/orifice. The pressure difference across the orifice will be gradually increased from 10 mmH_2O up to 180 mmH_2O at 10 mmH_2O per increase. The orifice pressure diwill represents the superficial velocity of the fluidizing gas. The conversion is represented by formula:

   Superficial Velocity, $V_{sup} = 0.140656\sqrt{Orifice\ Pressure\ Difference, \Delta P}$

   The particles used are shown in Figure 3.3 (a)-(d).

Big Sphere	**Irregular 1 (Flat)**	**Irregular 2 (Rice)**	**Small Sphere**
			
(a) d =3 mm	(b) l/d = 1.36	(c) l/d = 2	(d) d = 2 mm

Figure 3.3 (a) – (d) Particles Used for Experiment.

3. The distributor pressure drop and bed pressure drop will be measured using piezometric ring and the reading will be displayed in a Yokogawa transmitter.

4. The extension of annular area will be observed visually.

CHAPTER 4

RESULT AND DISCUSSION

4.1 Design Phase

4.1.1 Define Problem

The novel conceptual design generated must follow the basic principle stated by Vijay Raghavan [4] which is "Distributor must provides lower fluid velocities at the inner radius".

The benchmark selected is Kumar's distributor with triple rows and single rows of blades. According to Kumar, the area utilized in the single row distributor was less than the triple rows distributor, but the pressure drop in triple rows distributor is slightly higher than the single row distributor, this is due to the blade holders between the rows. [8]

4.1.2 Concept Generation

Sreenivasan and Raghavan's idea is translated by varying the insertion angle of the fluid when it enters the bed. The angle difference will affect the x and y components of the fluid velocity with regards to the radius, thus the swirling velocity achieved will vary accordingly. By varying the fluid velocity, it is expected that the particle massing will be significantly reduced and the annular area utilization can be massively increased.

- Utilizing blades with twisted profile
  The design is inspired by Kumar's triple row distributor [7]. It is designed to have a major modification on the blades dimension, shape and orientation. By twisting the blade, no holder between the rows will be required, thus the pressure drop will be reduced. The twist will also provide various insertion angle of the fluid, varying the velocity from inner to outer radius.

- Utilizing tubes in annular row
  The idea is to have several rows of small tubes to replace the distributor. The tubes will act as the gas injector to the bed. The tip of the tubes that enter the bed will be slanted at certain angle in which this angle will vary between each row.

By having this configuration, the velocity of the fluid insertion will vary accordingly from inner to outer radius.

4.1.3 Concept Evaluation

Table 2 shows the comparison between four different distributors. The benchmark used is Kumar's triple row and single row distributor

Table 2. Conceptual Design Benchmarking and Comparison

Twisted Blades	**Tubes in Annular Row**	**Kumar's Triple Row**	**Kumar's Single Row**
Advantages: • Novel Design • Possible to increase utilization area to be larger than single row distributor • No blade holder, reduce bed pressure drop	**Advantages:** • Novel Design • Possible to increase utilization area to be larger than single row distributor • No blade holder, reduce bed pressure drop	**Advantages:** • The amount of area usage is predicted to be larger than single row distributor	**Advantages:** • The pressure drop is lower than triple row distributor
Disadvantages: • Twisting the blade is a bit tricky • Research needs to be conducted to search the most feasible fabrication method	**Disadvantages:** • Expensive to manufacture/ purchase the tubes • The tubes will be too heavy to be supported by the existing SFB apparatus	**Disadvantages:** • The pressure drop is higher than the single row distributor due to blade holder	**Disadvantages:** • Particle massing • Dead zone at the center • Low area utilization

As a summary, the distributor with twisted blade is actually designed to fuse the advantages of triple row distributor and single row distributor. Not only it will increase the utilization area but also reduce the pressure drop of the distributor.

4.1.4 Configuration Design

- Distributor Components

The new distributor will have three main components, they are: inner ring, outer ring, and blades. There will be three kinds of blade to be fabricated- straight blades, forward blades, and backward blades. An experiment variation will be conducted to determine which blade configuration will give the best fluidization and utilization area. The distributor components were also designed so that the blades are detachable. This is to ease the assembly, simplify the manufacturing process, and reduce the fabrication cost.

- Determine the Angle of Twist

The angle of twist selected is 6^o. An angle as small as 6^o was pick at random to initiate the study on whether twisting the blade at a small angle can extend the useful annular area of SFB. This amount of twisting is also suggested by the fabricator judging that the twisting angle is within the capacity of the fabricator. Given the blade inclination angle to be 10^o, with blades twisted at 6^o, the inclination will vary to either 4 degree ($10^o - 6^o$) or 16 degree ($10^o + 6^o$). There will be three different blades to be fabricated, they are: flat blade, forward twist, and backward twist. This variation is to determine which profile will provide the best result.

- Dimensioning

The dimensioning of the twisted blade distributor will be set so that it will fit the best in current set up.

  - Blades

    The blades will all have the same dimension. It is designed to be longer than the current existing blades to test on the utilization area increase. The length of the blade is designed to be 100 mm, with 1 mm thickness.

  - Inner Ring

    To accommodate the new blade design, the inner ring size is made to be smaller than the current one used at the distributor. The outer radius will be

100 mm, inner radius will be 80 mm, thickness (top and bottom part, not including the blade) is 25 mm, and 10^o inclination angle. The outer diameter of 100 mm is selected at random as a starting number for area extension.

- Outer Ring

  The outer ring dimension will be the same with current existing outer ring. The outer radius will be 320 mm, inner radius will be 300 mm, and thickness (top and bottom part, not including the blade) is 25 mm.

- Material Selection

Material is selected by following the current existing SFB distributor, which is Aluminum. As the blades are designed to have thickness around 1mm, aluminum sheet ductility will ease the twisting process. While for aluminum block, it is quite rigid and undeformable, thus it suits best to be used for the inner and outer ring.

4.1.5 Detail Design

The detailed drawing for forward twisted blade is shown in Figure 4.1. The rest detailed drawings for the distributor component can be seen in appendix B.

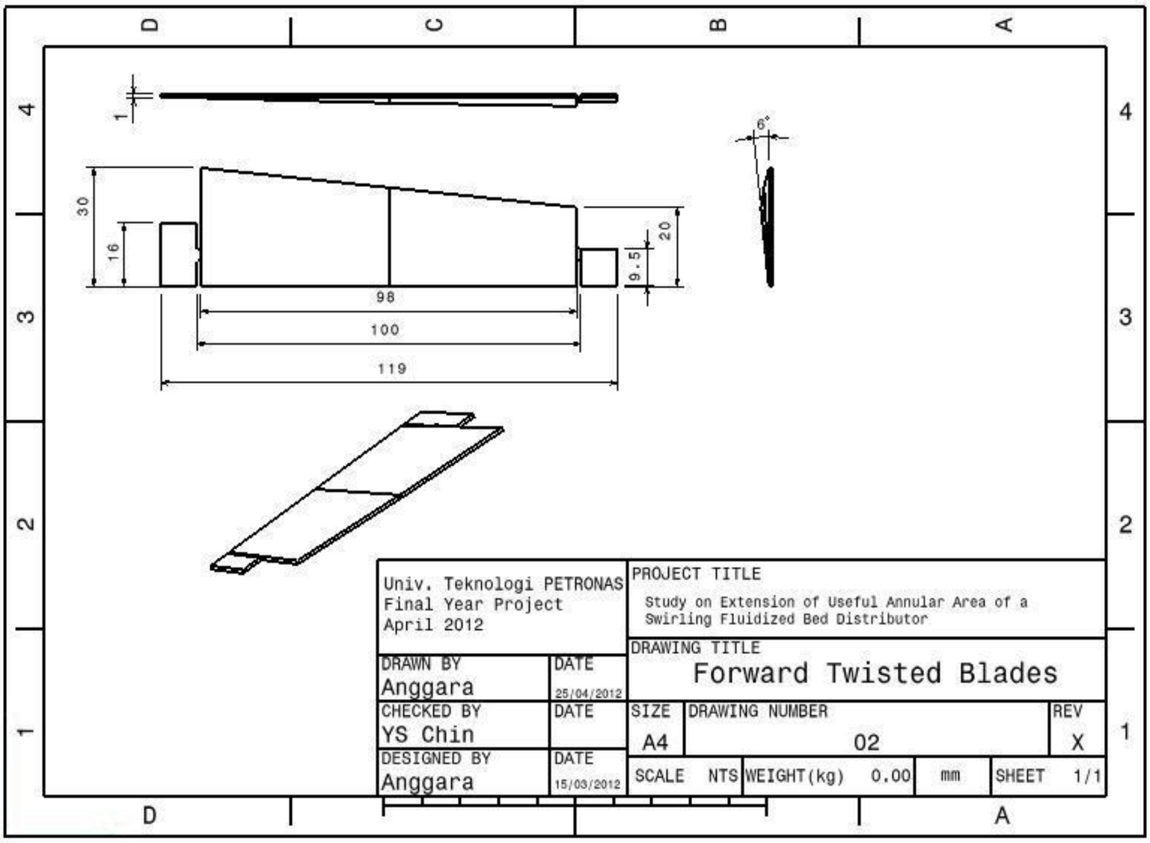


Figure 4.1 Detailed Drawing of Forward Twisted Blades

4.2 Fabrication Phase

4.2.1 Fabrication Method

The fabrication is a vital phase. An excellent design will not be accepted if there is no possible fabrication method to create the prototype. For the distributor with twisted blades, the possible fabrication methods are as follows:

- Inner and Outer Ring

Cutting and Shaping by using EDM Wire Cutter machine.

- Blades

There are three possible methods of fabrication as shown in Table 3.

Table 3. Fabrication Methods Comparison

EDM Cutting – Die Stamping	EDM Cutting – Manual Twisting	Sand Casting
First, blades are cut into shape by using EDM wire cutter. Then a die stamping will be used to produce the blades.	First, blades are cut into shape by using EDM wire cutter. Blades are then placed in between two clamped ends and manually twisted.	By using sand casting, each blade will be casted into shape from molten metal.
Advantages: • High production rate **Disadvantages:** • Expensive tooling , not feasible to fabricate only three sets of blades	**Advantages:** • Inexpensive and high production rate **Disadvantages:** • Less precise • A good and reliable control measure must be conducted to increase the precision	**Advantages:** • Simple, only one process of casting needed to produce all parts needed (blades, inner and outer rings). **Disadvantages:** • Expensive • Smooth finishing will be time consuming

From Table 3 the most feasible method in term of time and cost is manual twisting. To ensure the accuracy of the twist, a lathe machine is used. Without turning the machine on, the clamps are placed in chuck and tailstock. A scale is drawn in the chuck to measure the amount of twisting. The angle of twist is calculated based on the ratio of chuck circumference and the circumference of the twisted angle.

Given that the chuck diameter is 350 mm, thus the circumference will be 1099 mm. In order to produce 6 degree of twist, the chuck must be turned 18.2 mm. This number comes from the calculation of $(6^o/360^o)*1099$ mm.

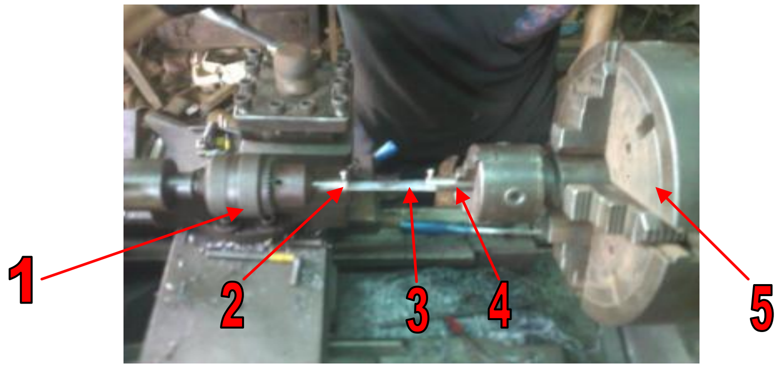


Figure 4.2 Configuration of Manual Twisting with Lathe Machine: 1. Tailstock, 2.Clamp, 3. Blades, 4. Clamp, 5. Chuck

Figure 4.3 Clamps Used in Fabrication Process. Material is Mild Steel with Length of 76 mm, Notch Length is 19 mm and Width 1 mm

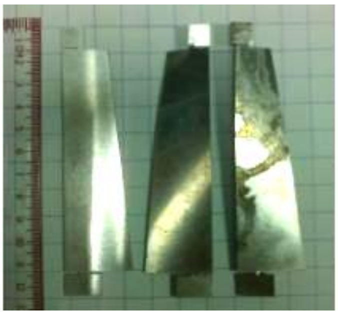


Figure 4.4 The Blades to be Fabricated (From Left to Right): Straight Blade, Forward Twisted Blade, and Backward Twisted Blade

4.3 Experiment Results

4.3.1 Regimes of Operation and Bed Hydrodynamic Analysis

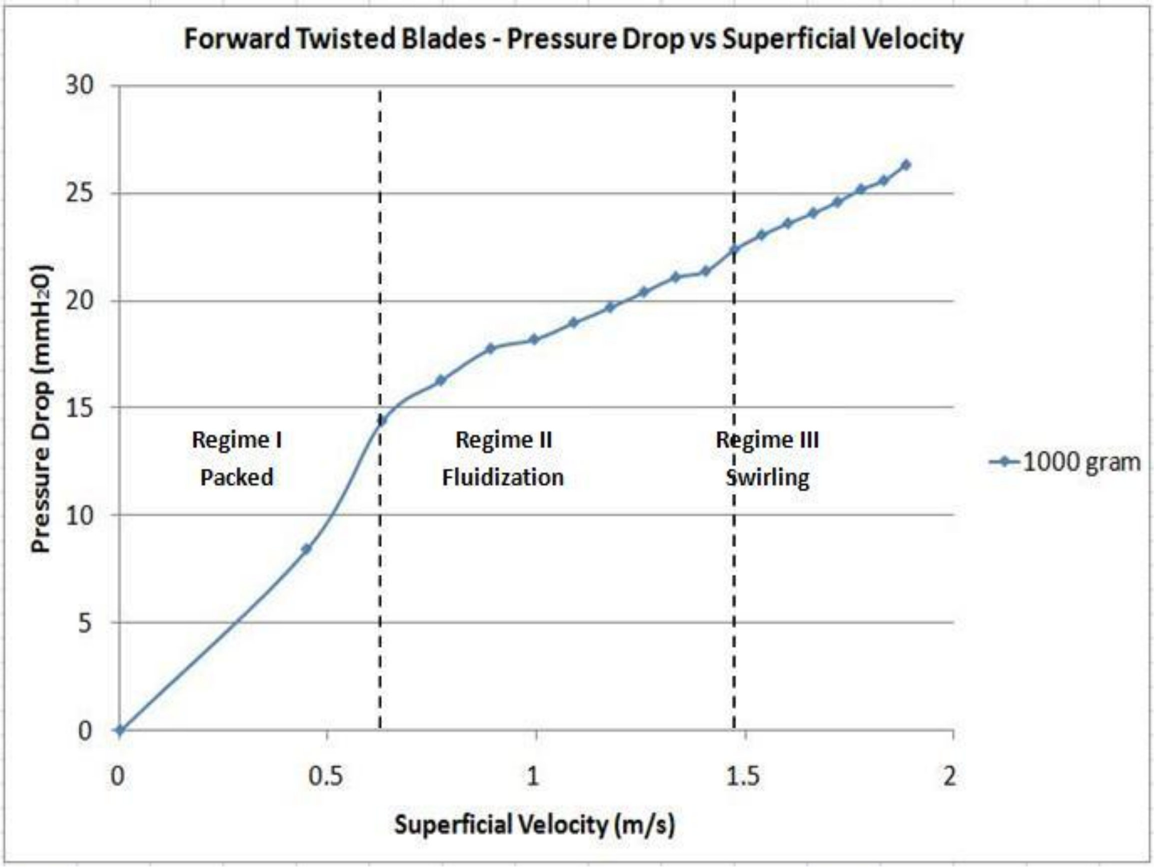


Figure 4.5 Pressure Drop vs Superficial Velocity Graph for 1000 g Bed Loading of Spherical 3 mm-diameter Particles in Distributor with Forward Twisted Blades

The distributor with forward and backward twisted blades shows the same operation regimes for shallow bed (1000 g). In Figure 4.5 the flow regime of distributor with forward twisted blades and 1000 g bed loading is shown. The packed regimes existed between superficial velocity 0 – 0.77 m/s (orifice pressure drop at 0-30 mmH_2O). The bed shows the sign of minimum fluidization at superficial velocity 0.89 - 0.99 m/s (orifice pressure drop at 40-50 mmH_2O). At the same superficial velocity, bubbling starts and continued with slugging until the velocity of 1.48 m/s (orifice pressure drop 110 mmH_2O) is reached. However, for distributor with forward twisted blades, there is no sign of particle elutriation even when the superficial velocity has reached the maximum level, given by the maximum flow rate the blower can supply.

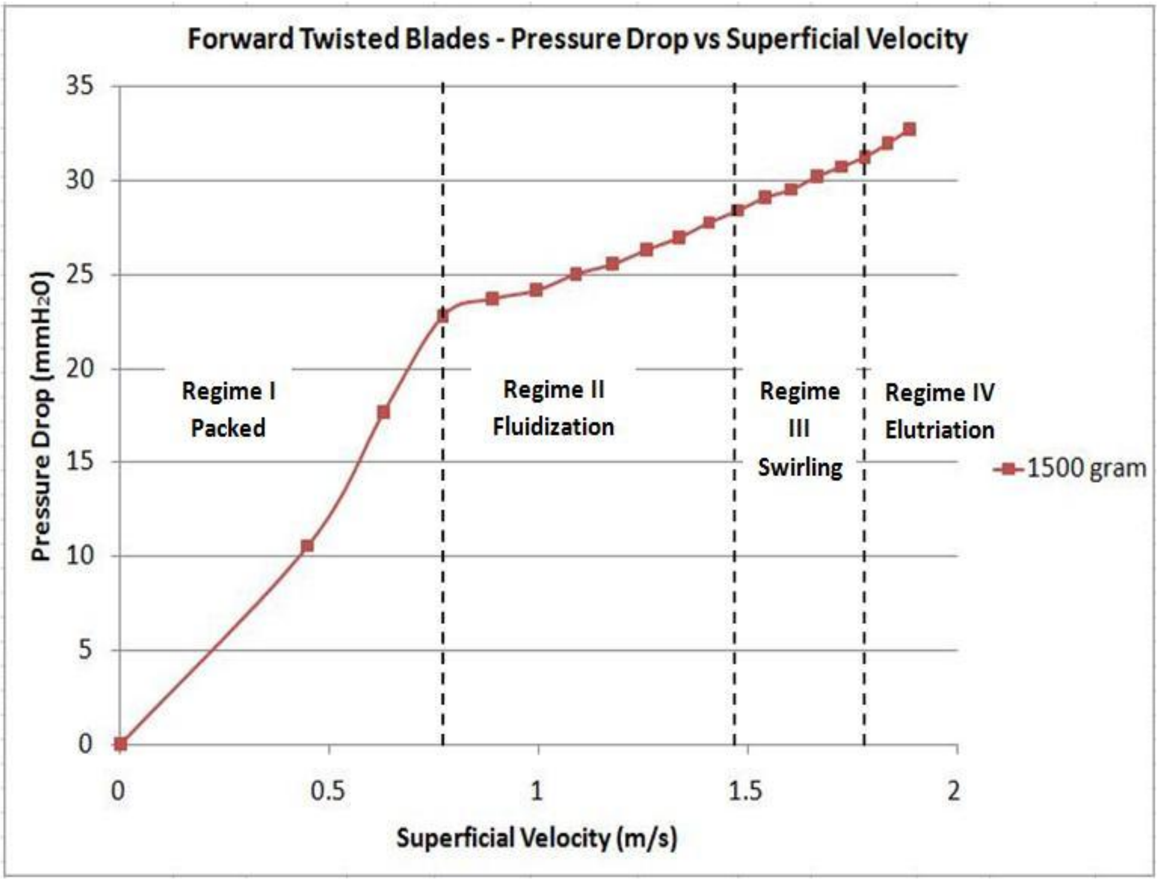


Figure 4.6 Pressure Drop vs Superficial Velocity Graph for 1500 g Bed Loading of Spherical 3 mm-diameter Particles in Distributor with Forward Twisted Blades

For deeper bed (1500 g and 200 g) the same phenomenon was also observed in the distributor with backward twisted blades, implying both the distributor forward and backward twist show the same regimes. Between the superficial velocity 0 – 0.77 m/s (orifice pressure drop at 0-30 mmH_2O), the bed is still in packed regime. The fluidization first occurs at 0.89 m/s (orifice pressure drop at 40 mmH_2O), where the bubbling starts and followed by slugging when the pressure is gradually increased. Further increase of the fluidizing gas will result the particles to bubbling in more vigorous way until it reaches the minimum swirling at superficial velocity of 1.48 m/s (orifice pressure drop of 110 mmH_2O). Quite differently with SFB that utilizes straight blades for its distributor, the swirling that occurs at SFB with twisted blades distributor is more vigorous, but it does not show the two layers of swirling and bubbling. Particle swirls in the same direction but in a more vigorous manner and jumpy, especially in the area near the center cone. The rigorousness becomes stronger and at superficial velocity of 1.78 m/s (orifice pressure drop of 160 mmH_2O), the particles start flying out of the bed.

4.3.2 Effect of Various Bed Configuration

A. Effect of The Blades Twist Orientation

Figure 5.7 below shows the bed pressure drop for three different distributors used in the experiment. The pressure drop was measured in dry run condition, where no particle was loaded into the bed.

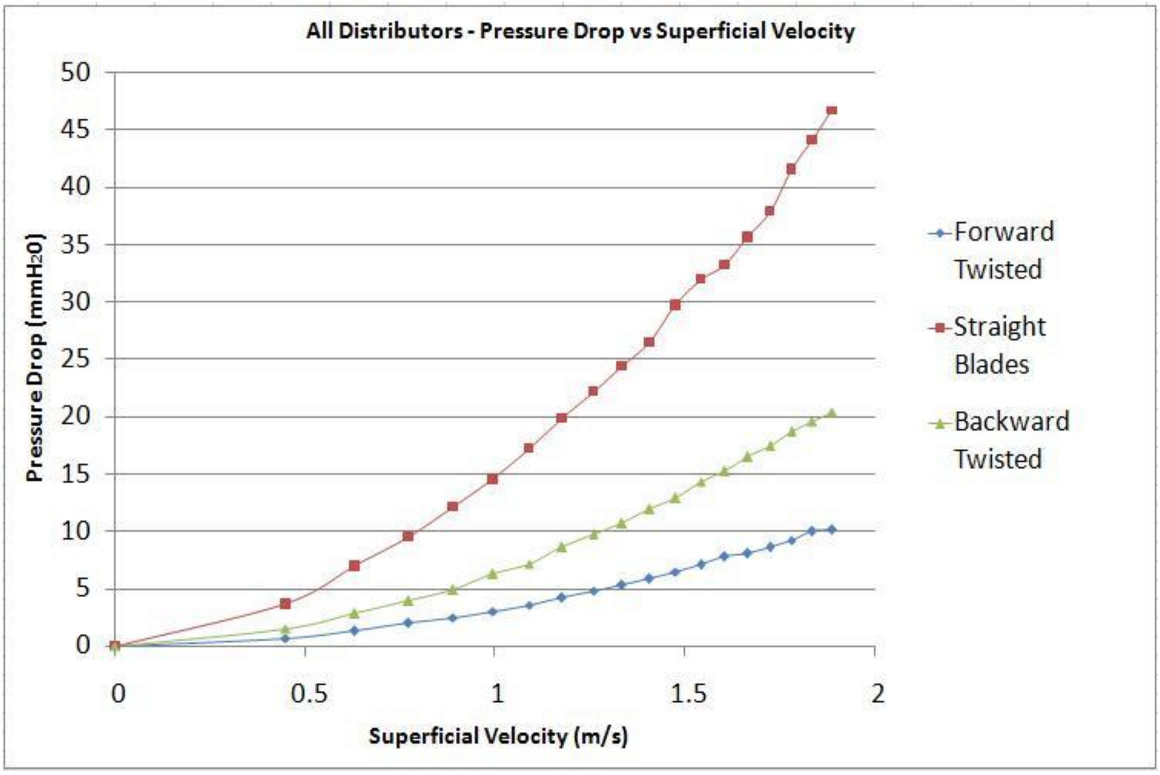


Figure 4.7 Distributor Pressure Drop vs Velocity Graph of Distributor with Straight, Forward Twisted, and Backward Twisted Blades with No Bed Loading

Figure 5.7 shows that the pressure drop for both the distributor with forward twisted and backward twisted blades are much smaller than the pressure drop for straight blades. For straight blades, the effect of longer dimension will cause higher pressure drop in its operation. Comparing straight blades with the twisted blades, the pressure drop of distributor with straight blades is higher than those of the twisted blades.

For any distributor, the difference in pressure (pressure drop) is mainly due to the fluidizing gas velocity after passing through the distributor. The variation of blade angle from inner to outer side of the distributor provided by twisted blades has proven to produce lower gas velocity at the distributor exit compared to the straight blades. Lower velocity produces higher pressure. Thus, the pressure of the fluidizing gas before entering the distributor (pressure at plenum chamber) and after the gas exits the distributor will only be slightly reduced.

To reduce the pressure drop, the straight blade must be twisted so it will compensate the increment of the bed pressure drop. This fact shows that distributor with twisted blades is superior to distributor with straight blades, especially in terms of energy usage efficiency. Faizal Mohideen et al. [2] confirmed that the higher the pressure drop means higher potential energy required for fluidization process.

Figure 5.7 also indicates that among the two distributors with twisted blades, the distributor with forward twist blades is more superior compared to distributor with backward twist blades. The forward twisted blades produce 50% lower pressure drop than backward twisted blades.

B. Effect of The Bed Weight

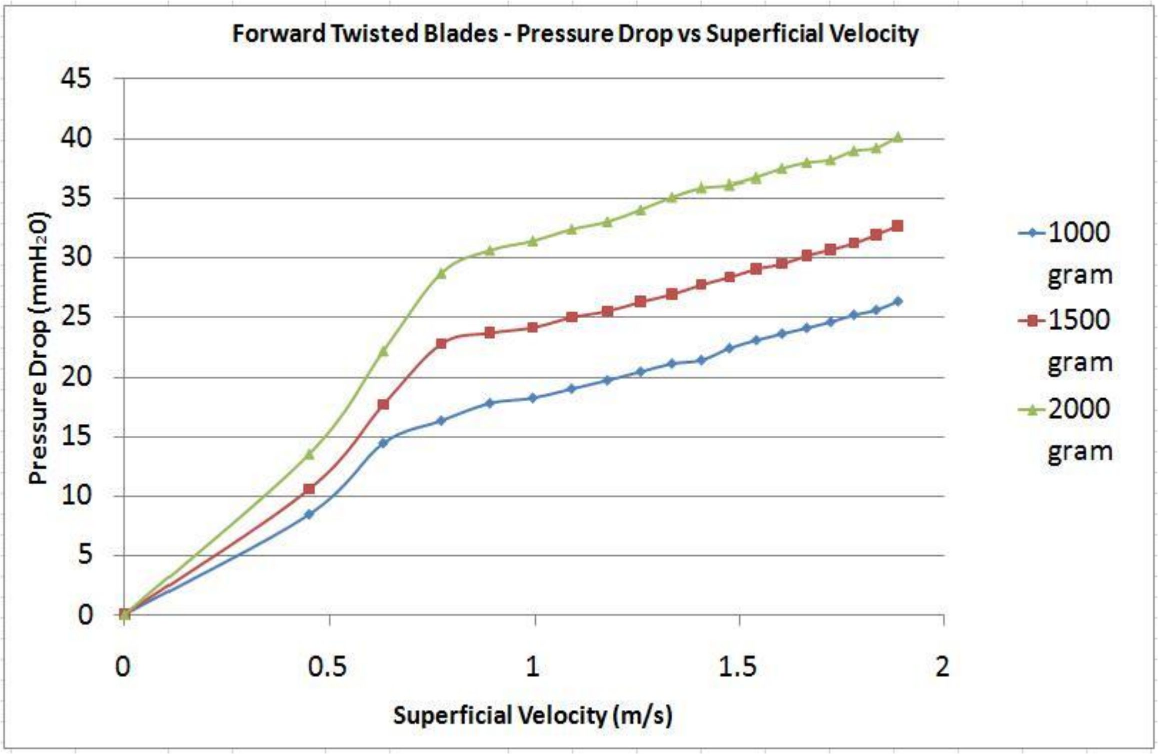


Figure 4.8 Pressure Drop vs Velocity Graph of Spherical 3mm-diameter Particle for Distributor with Forward Twisted Blades under Three Different Bed Loadings

Figure 5.8 shows that the amount of bed weight plays an important effect on the bed pressure drop. The bed loading were increased gradually from 1000 g, 1500 g, to 2000 g to investigate the effect of additional loading to the pressure drop. The pressure drop is seen to be linearly correlated to the pressure drop. Higher bed weight will result in higher pressure drop. The reason is that the higher centrifugal bed weight, more particles are present inside the bed, and thus there will be more wall friction as proposed by [2]. Wall friction will cause larger pressure drop as being indicated by graph in Figure 5.8.

C. Effect of Particle Size and Shape

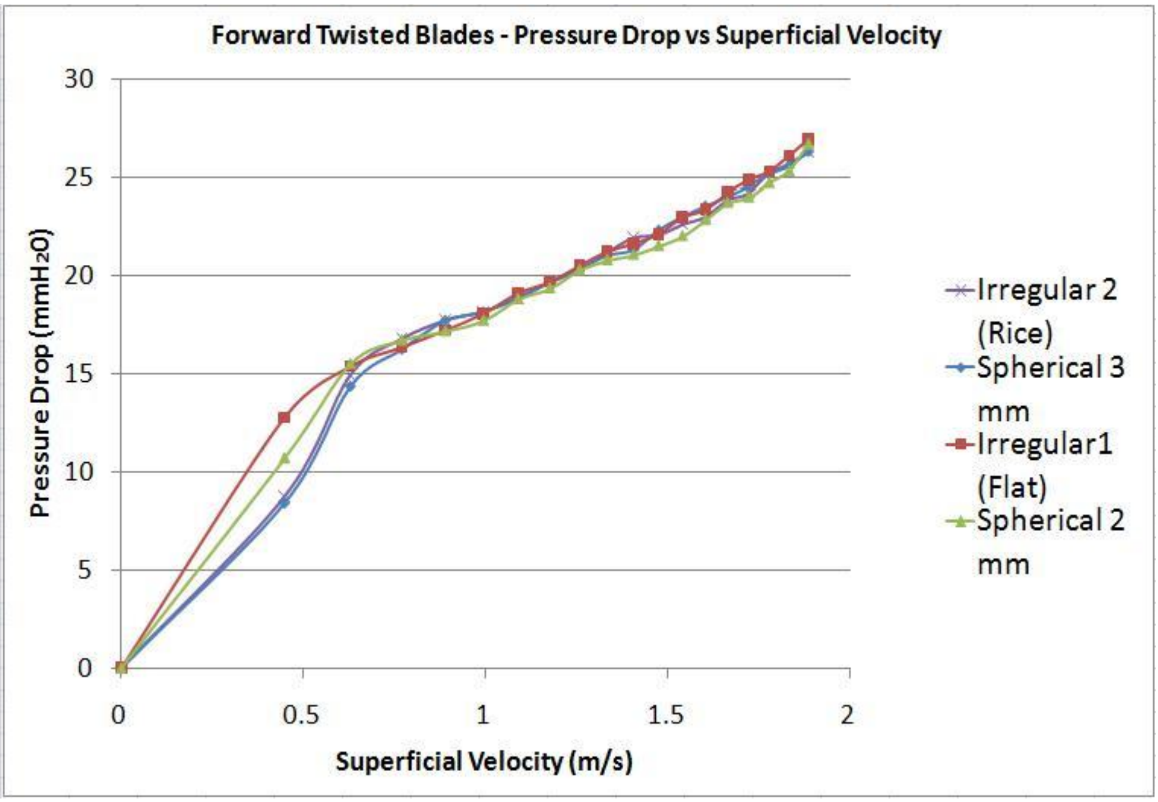


Figure 4.9 Pressure Drop vs Velocity Graph of 1000 g Bed Loading for All Particles in Distributor with Forward Twisted Blades

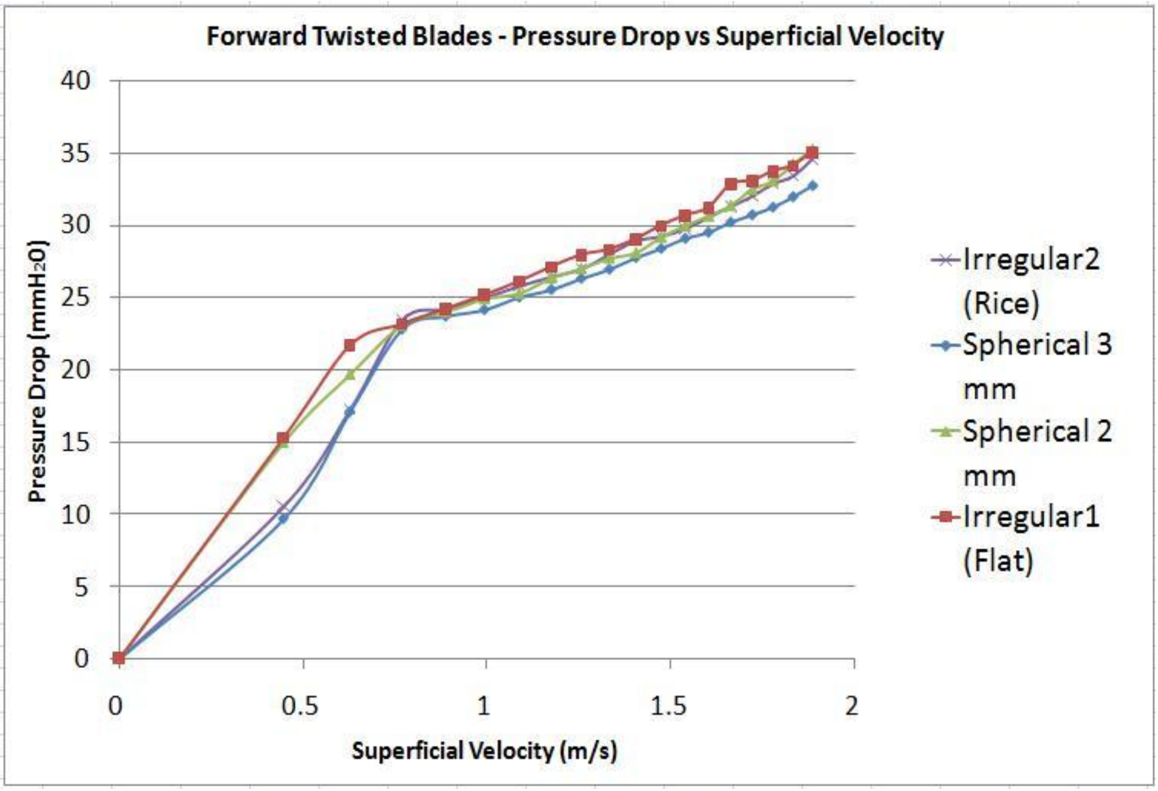


Figure 4.10 Pressure Drop vs Velocity Graph of 1500 g Bed Loading for All Particles in Distributor with Forward Twisted Blades

Experiments were conducted using four different particles to determine the effect of particle geometry on the distributor with twisted blades. It can be seen from Figure 5.10 that for both twist orientations, the pressure drops were higher in the packed regions, and larger particle diameter will cause lower pressure drops. The least pressure drop were produced by big sphere particles (3 mm diameter), followed by irregular-rice particles (l/d ratio is 2), small sphere particles (2 mm diameter), and the highest pressure drop were produced by irregular-flat particles (l/d ratio is 1.36). According to Faizal Mohideen et al. [2], smaller particles will cause higher pressure drop because smaller particle actually have larger surface area per volume. In this case, eventually, the largest surface area belongs to the irregular-flat particles.

On the contrary with [2], for distributor with forward twisted blades, once the bed has reached the minimum fluidization, the pressure drop reading indicates that the difference in pressure drop between one particle and another is not that much. This proves that the effectiveness of distributor with forward twisted blades is not affected by the particle size. It is equally effective for fluidization of any particle.

4.3.3 Annular Area Utilization

From visual observation, the twisted blades provide the best swirling condition at superficial velocity 1.48 m/s (orifice pressure drop is 110 mmH_2O) and bed weight of 1000 g. This condition was observed wherein:

a. The particles were calmly swirling and did not go jumpy

b. Only one flow regime was present, which was swirling

c. Least vacant space at the center of the distributor

Figure 5.11 (a)-(c) show the stop motion pictures of 1000 g big sphere particles (3 mm diameter) swirling at superficial velocity of 1.48/ m/s (orifice pressure drop at 110 mmH_2O). The big sphere particles were chosen because these particles produce the least pressure drop, thus make it ideal for comparison

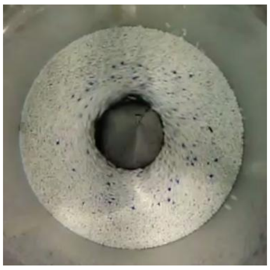
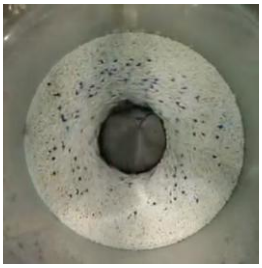
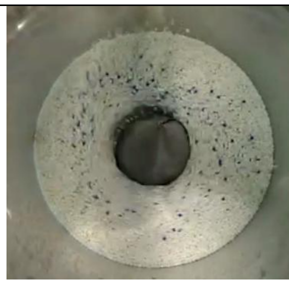
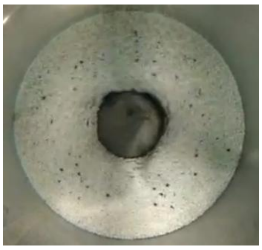
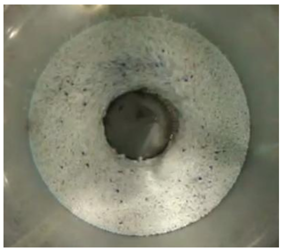
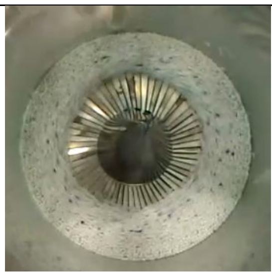
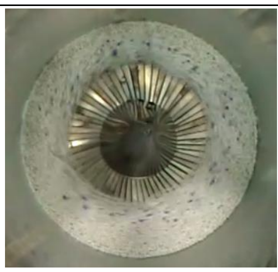
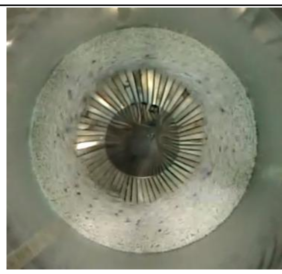
Forward Twisted Blades (a)			
Backward Twisted Blades (b)			
Straight Blades (c)			

Figure 4.11 (a)-(c) Top View of Annular Area Utilization for Distributor with Different Blades Orientation at Superficial Velocity 1.48 m/s (Orifice Pressure Drop at 110 mmH_2O), Bed Weight 1000 g, Spherical Particles with 3 mm-diameter

Figure 5.22 (a)-(c) show other sets of stop motion pictures on fluidization of big sphere particle in distributor with forward twisted bed for higher bed weight (1500 g) at superficial velocity 1.48 m/s (orifice pressure 110 mmH_2O).

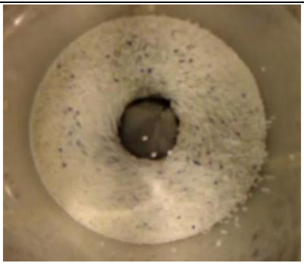
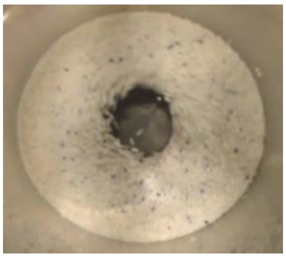
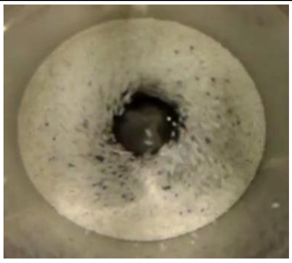
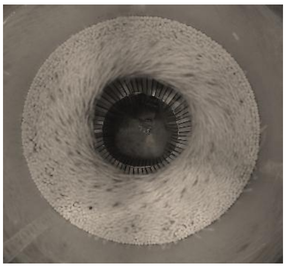
Forward Twisted Blades (a)			
Backward Twisted Blades (b)			
Straight Blades (c)			

Figure 4.12 (a)-(c) Top View of Annular Area Utilization for Distributor with Different Blades Orientation at Superficial Velocity 1.48 m/s (Orifice Pressure Drop at 110 mmH_2O), Bed Weight 1500 g, Spherical Particles with 3 mm-diameter

From Figure 5.11 and 5.12 can be seen that the distributor with forward twisted and backward twisted blades utilize more annular area compared to distributor with straight blades. The annular vacant area for forward and backward twisted blades was observed to be around 0 cm - 1.5 cm diameter from the center cone. This gives annular area utilization number at 96% - 100% of the available area. It is higher if we compare it with the distributor with straight blades where swirling only presents at annular area where the diameter is between 5 cm – 6 cm from the center cone, occupying 76%-84% of the available area. For shallow bed (1000 g), it was observed that when the superficial velocity is increased, the size of annular vacant area around the center cone is getting larger. The annular vacant area on the bed with more load (1500 g and 2000 g) also observed and the size of the annular vacant area was reckoned to be smaller.

Area increment was observed to be affected by the blade twist. The twist varies the insertion angle of the fluidizing gas when it enters the bed. The angle difference affects the x and y components of the fluid velocity with regards to the radius, thus the swirling velocity achieved will vary accordingly. The forward twist provides such an angle in which the velocities at inner radius is smaller compared to the outer ones. This velocity is sufficient enough to swirl the particles without causing further massing.

The utilization area is important feature of SFB because it is closely related to efficiency. Larger area utilization means more particles can achieve perfect swirling at the same amount of time. This will reduce the potential energy required to achieve swirling. The large area utilization will play an important role especially when it comes to industry application. Larger utilization area can be translated as higher capacity of the SFB reactor, which means more material can be processed at the same time, thus reduces the operation cost and increase production efficiency.

4.3.4 Fabrication Result

A. Inner and Outer Ring

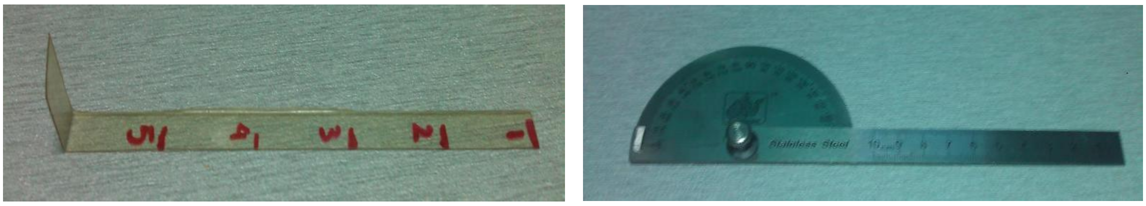
The process to fabricate the inner ring took the longest time in which the problem was to find the fabricator. There are only limited number of fabricators in the area could execute the design at reasonable price and time. Once we found the right fabricator, it only took 2 weeks for the inner ring to be finished.

B. Blade Twisting

After the fabrication complete, it turned out that the space for the front ear of the blade at the inner ring is only 4.5 mm. The early blade design requires 9.5 mm space for the blade front ear, and thus a design alteration must be carried out. The extra portion of the front ear must be reduced into 4 mm by using a shear metal cutter.

The twisting process that was done manually using lathe machine as mentioned before has shown to be fairly accurate. To assess the accuracy of the twist, the blades were first assembled into the inner and outer ring. After that, the gap between one blade and another were measured. The gap was designed to be 1 mm at point number 2, 2mm at point 3, and 3 mm at measurement point number 5 (refer to Figure 5.13).

Figure 4.13 Gap Measurement between One Blade and Another at Point 1,2, and 3 of The Sampler



(a) (b)

Figure 4.14 Gap Measurement Tools : (a) Sampler, (b) Ruler

From 360 points of measurement (for forward twisted and backward twisted blades), there were 68 points that was found to have gap smaller or bigger than the designated dimension. These differences ranging from ±0.5 mm up to ±1 mm. The measurement shows that only 19% of the measured points to be inaccurate according to the design. This can represent the accuracy of manual twisting process, which is only 81%.

The lack of accuracy was already predicted, it was due to the inaccuracy when manually turning the chuck at exactly 18.2 mm. The material ductility also affects the precision, when the blade was twisted, the material tend to back to its original shape. This will affect the uniformity between one blade and another, because the amount of elastic recovery may vary from one blade to another.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The distributor with twisted blades is a completely new idea and has never been carried out before in the study of Swirling Fluidized Bed. The twisted blade design is expected to give a better performance of fluidization in terms of low pressure drop and high annular area utilization. Comparing to Kumar's distributor, the expected performance of the distributor with twisted blades will result in pressure drop as low as single row distributor and utilization area as much as triple row distributor.

Both the distributor with twisted blades has proven to be superior compared to the distributor with straight blades. The pressure drop is much smaller and the utilization area is much higher. It renders higher efficiency of the distributor with twisted blades to be used in SFB compared to distributor with straight blades. Among the two distributors with twisted blades, the distributor with forward twisted blades is the most superior. Even though the utilization area is the same, the forward twisted blades produce lower pressure drop on the bed. This implies lower potential energy is required to achieve same level of fluidization, yielding superiority of forward twisted blades to backward twisted blades. The pressure drop readings for different particle size and shape have shown only slight deviation between one particle and another. This means that the distributor with forward twisted blades is equally effective to be used for any particle fluidization.

The manual twisting method done using lathe machine has proven to be fairly accurate to fabricate the twisted blades. The gap consistency measurement shows that only 19% of the gap is wider/smaller than designed gap. It proves the accuracy of manual twisting method at 81%.

5.2 Recommendation for future work

In the future, there are still a few things that can be improved for the SFB that utilizes distributor with twisted blades, they are:

1. Run experiments on other angle of twist, preferably higher and investigate the effect on the bed hydrodynamic.

2. Run experiments using other particle size, shape, and bed weight to observe the effect on the bed hydrodynamic.

3. Find and apply new twisting method with higher accuracy, so it will produce uniform blades and increase area utilization further.

4. Apply the distributor with twisted blades into a multistage swirling fluidized bed to increase the productivity.

REFERENCES

[1] J. Shu, V.I. Lakshmanan, C.E. Dodson "Hydrodynamic study of a toroidal fluidized bed reactor" in *Elsevier Journal: Chemical Engineering and Processing*, Vol. 39, Issue 6, 1 November 2000, Pages 499–506.

[2] M. Faizal, V.Vinod Kumar, and V. R. Raghavan, "Experimental Studies on a Swirling Fluidized Bed with Annular Distributor" in *Int. Conference on Plant, Equipment and Reliability*, Kuala Lumpur, Malaysia, June 15-17, 2010.

[3] B. Sreenivasan, & V.R. Raghavan, "Hydrodynamics of a Swirling Fluidised Bed" in *Chemical Engineering and Processing*, Vol. 41, p. 99-106, 2002.

[4] G. Vikram, V.R. Raghavan, H. Martin, "A model for the Hydrodynamics of Swirling Fluidized Beds" in *4th International Conference for Conveying and Handling of Particulate Solids*, Budapest, Volume 1, 7.1, 2003.

[5] V.R. Raghavan, Prof. Dr. (private communication), 22 January 2012.

[6] S.C. Saxena, A. Chatterjee, R.C Patel. "Effect of distributors on Gas-Solid Fluidization" in *Powder Technology, Vol. 22,* 1979, p. 191-96.

[7] J.W. Hiby. 1967. "Periodic Phenomena Connected with Gas-Solid Fluidization" in *International Symposium on Fluidization*, Eindhoven, 1967, p. 99.

[8] V Vinod Kumar, Mohd.Faizal and Vijay.R.Raghavan, "Study of the Fluid Dynamic Performance of Distributor Type in Torbed Type Reactors" in *Engineering e-Transaction* (ISSN 1823-6379), Vol. 6, No.1, June 2011, pp 70-75.

[9] S. Harish Kumar, D.V.R. Murthy, "Minimum superficial fluid velocity in a gas–solid swirled fluidized bed" in *Chemical Engineering and Processing*, Vol. *49*, 2010, p.1095–1100.

[10] G.E. Dieter and L.S. Smith, *Engineering Design*. New York : McGraw-Hill Higher Education, 2008.

[11] S. Kalpakjian and S.R. Schmid, *Manufacturing Engineering and Technology*. New York : Prentice Hall, 2009.

[12] T.R. Vijayaram. (2009, Jan.). "*Electric Discharge Machining for Metal and Alloys"*[Online]. Available: http://www.themetallurgist.co.uk/articles/edm_of_metals_and_alloys.shtml [Accessed March 15, 2012].

[13] IEEE Computer Society. (2007, Nov.). *"IEEE Computer Society Style Guide – References"* [Online]. Available: tinyurl.com/ypdfts [April 25, 2012].

APPENDIXES

Appendix A - Gantt Chart and Project Milestones

Appendix B – Detailed Design of Distributor Components

Appendix C - Data Collected for Distributor with Forward Twisted Blades

Appendix D - Data Collected for Distributor with Backward Twisted Blades

Appendix E - Data Collected for Distributor with Straight Blades

Appendix F – Pictures of Distributor with Forward Twisted Blades, Backward Twisted Blades, and Straight Blades

Appendix A - Gantt Chart and Project Milestones

FYP 1

No	Detail/Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14	Key Milestone (•)
1	Topic Selection		•														Topic Selection (Week 2)
2	Preliminary Study						•										Extended Proposal Submission (Week 6)
3	Design																
	• Determine the angle of twist										•						Proposal Defense Presentation (Week 9)
	• Sketch the distributor																
4	Fabrication																
	• Inner & Outer Ring																
	• 1st set																
	• 2nd set															•	Interim Report Submission (Week 14)

FYP 2

No	Detail/Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14	15	Key Milestone (•)
1	Fabrication																	
	• 2nd set																	
	• 3rd set			•														Finish Fabrication (Week 3)
2	Experiment							•										Finish Experiment (Week 7)
	Variation on bed weight,																	
	particle size,																	
	and particle shape																	
3	Result Analysis									•								Progress Report Submission (Week 8)
4	Reporting													•				Draft of Final Report Submission (Week 12)
																•		Oral Presentation (Week 14)
																	•	Hard Bound Final Report Submission (Week 15)

Appendix B – Detailed Design of Distributor Components

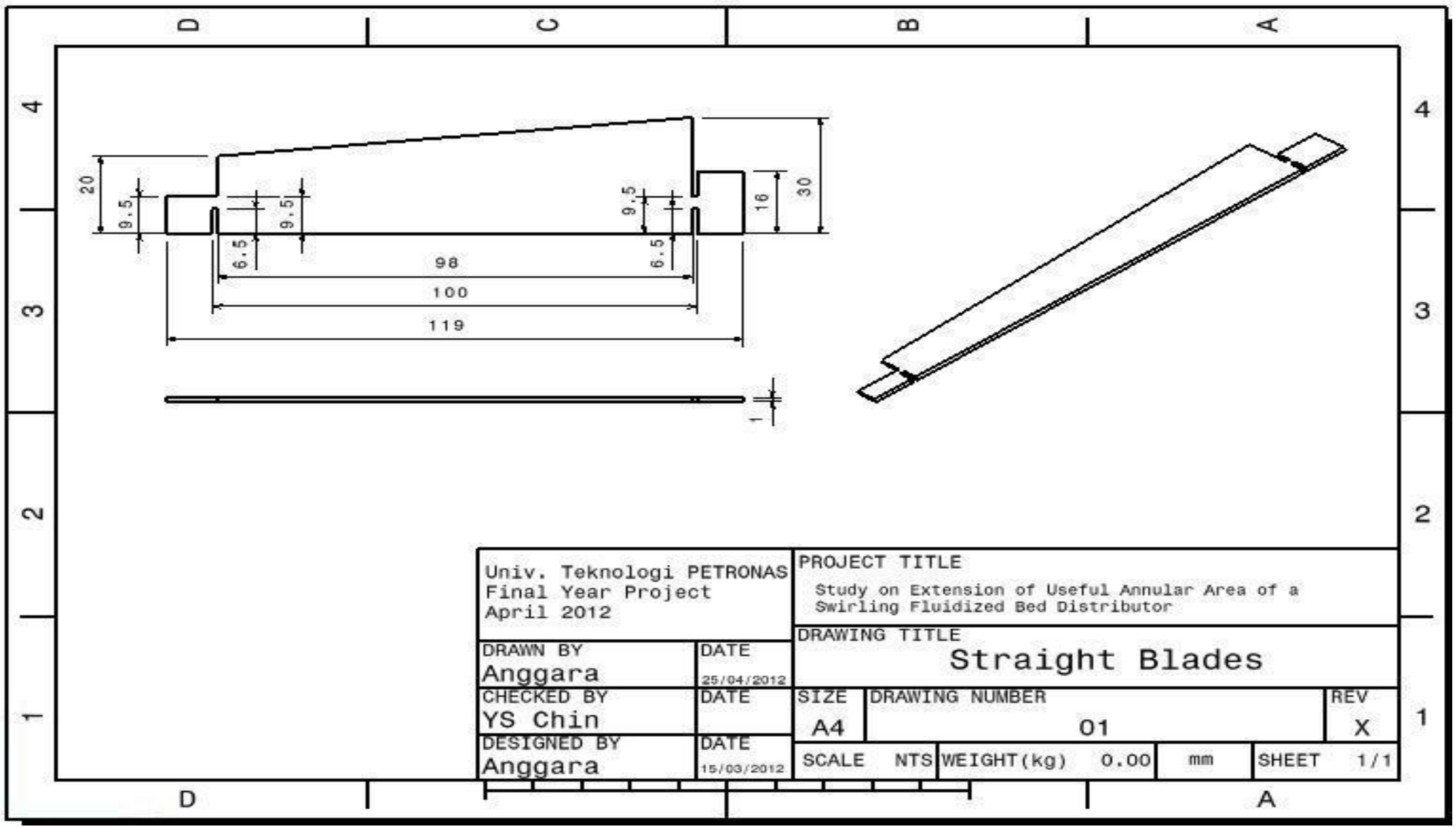


Figure B1 - Detailed Drawing of Straight Blades

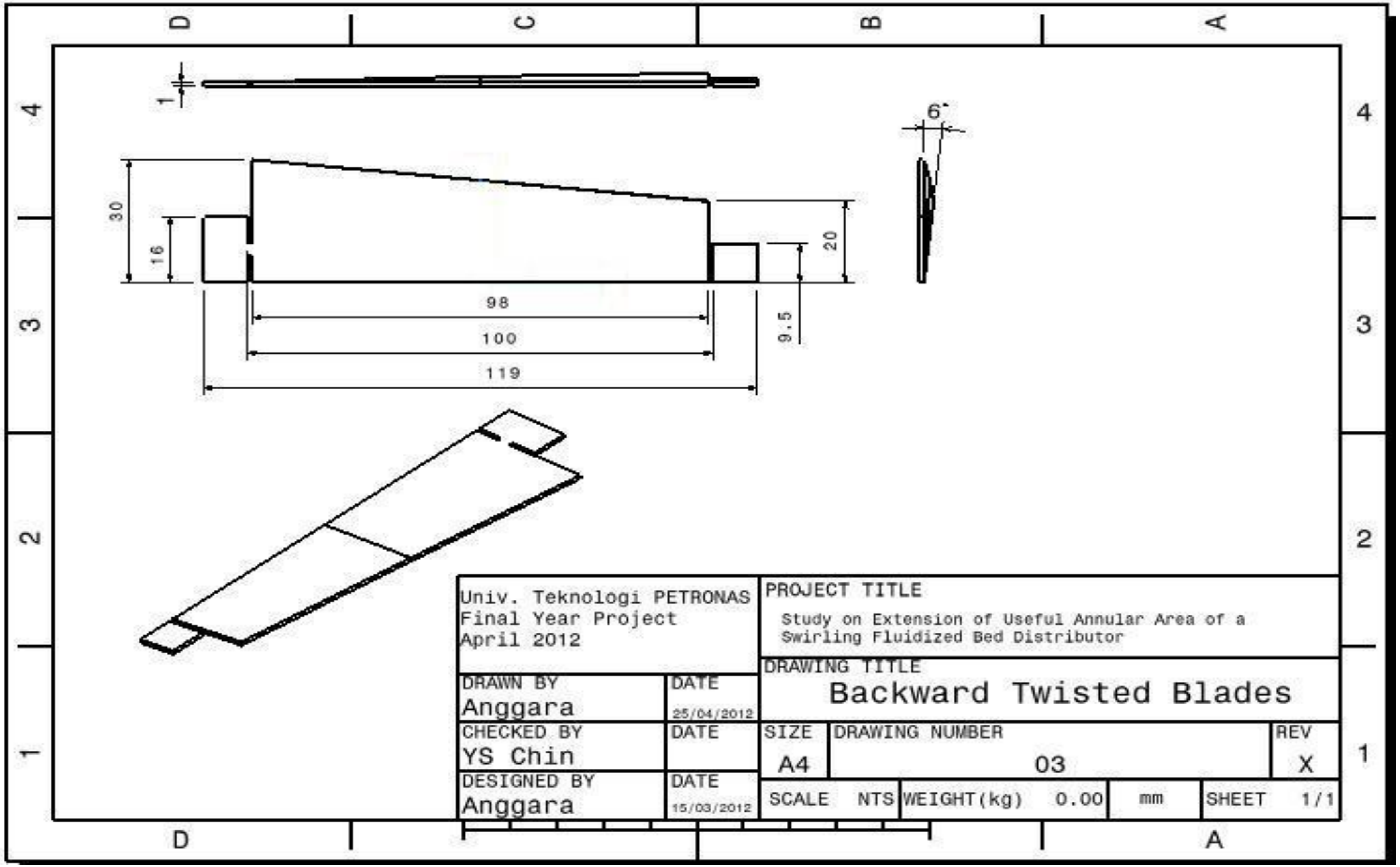


Figure B2 - Detailed Drawing of Backward Twisted Blades

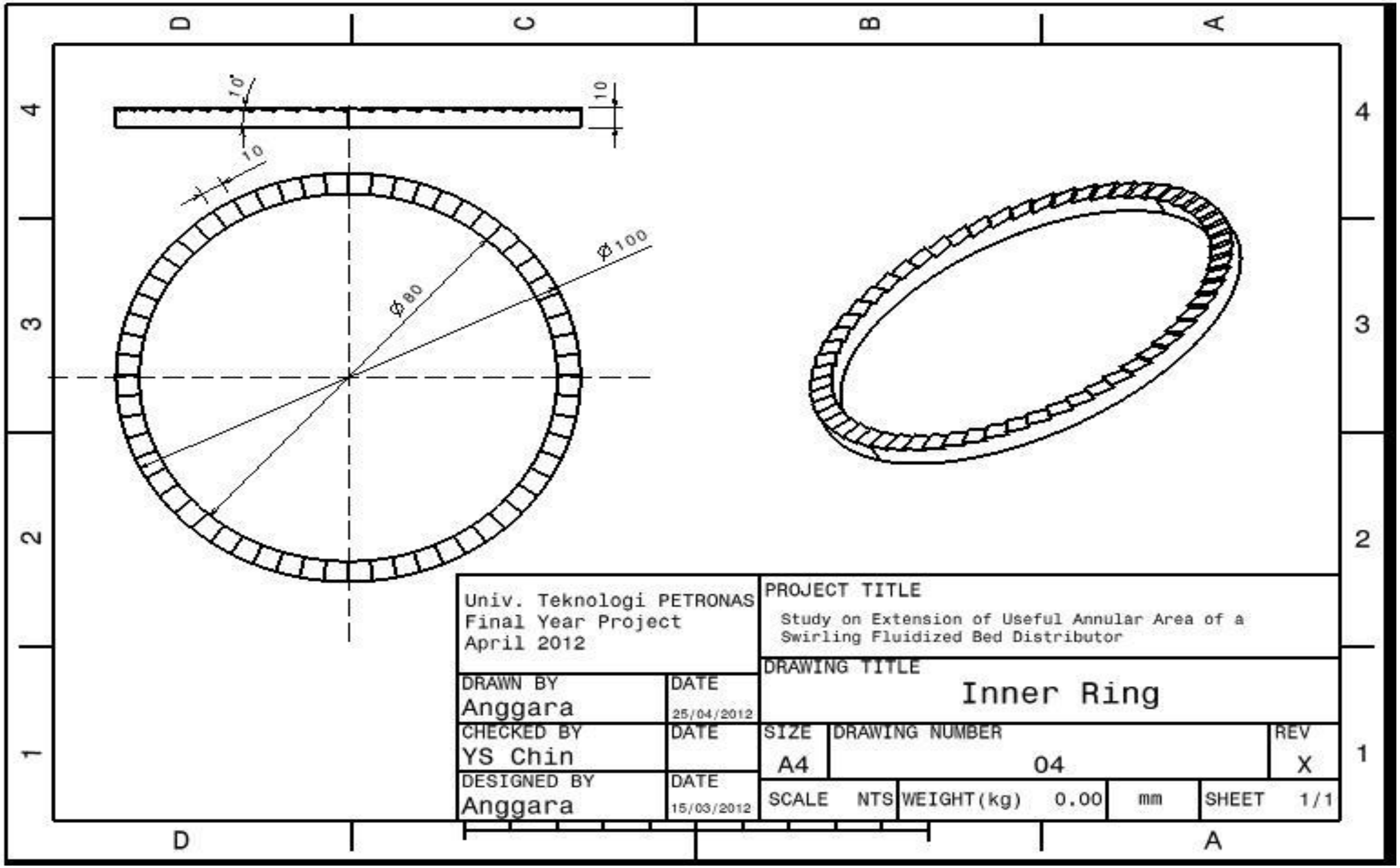


Figure B3 - Detailed Drawing of Inner Ring

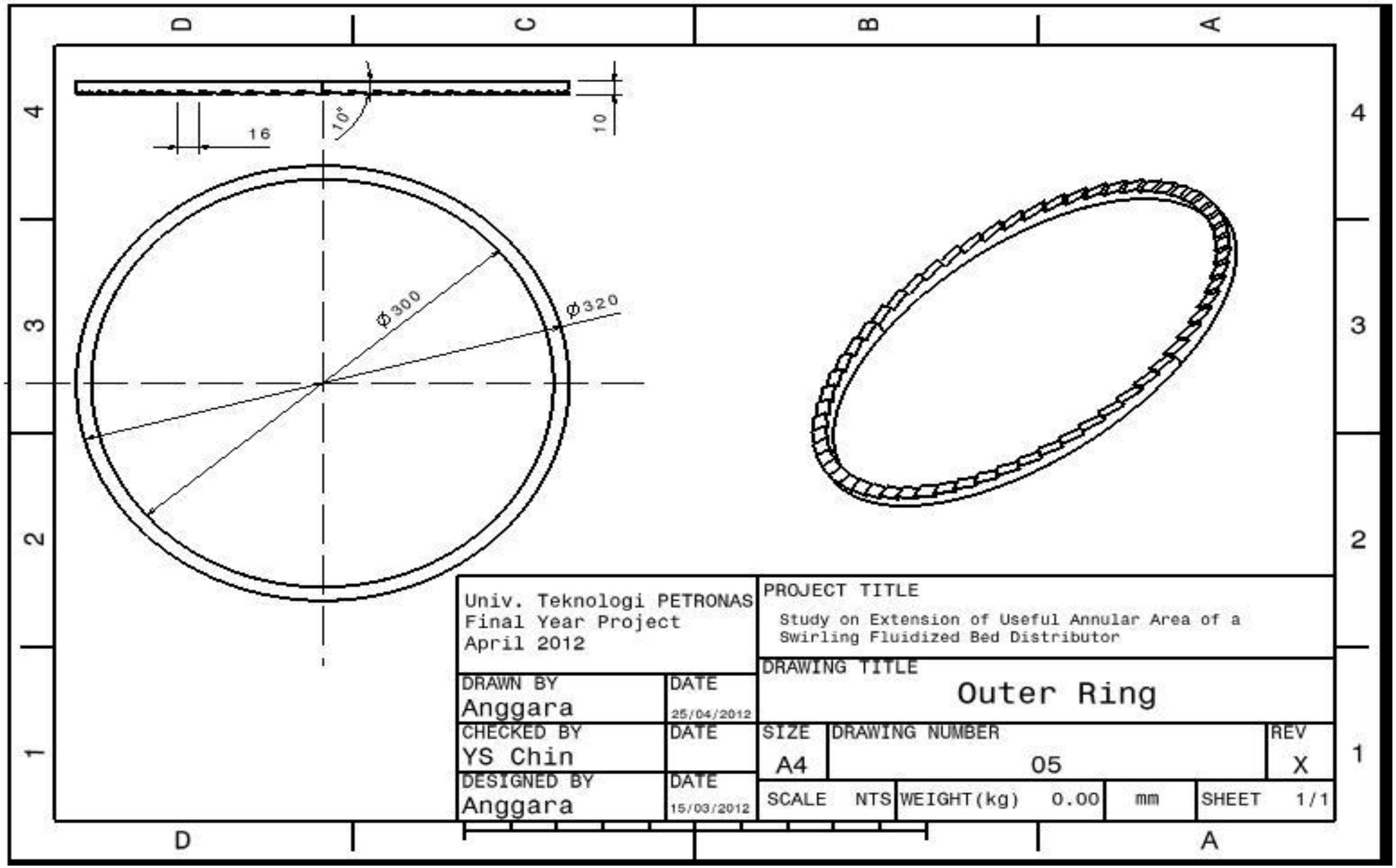


Figure B4 - Detailed Drawing of Inner Ring

Appendix C - Data Collected for Distributor with Forward Twisted Blades

Orifice Pressure Drop	P2-P3	P1-P3	Regime	P1-P3	Regime	P1-P3	Regime	P1-P3	Regime	P1-P3	Regime	P1-P3	Regime	Superficial Velocity
mmH2O	empty bed	1 kg, spherical 3 mm		1.5 kg, spherical 3 mm		2 kg, spherical 3 mm		1 kg, irregular1 (flat)		1.5 kg, irregular1 (flat)		2kg, irregular1 (flat)		m/s
10	0.7	8.42	-	9.71	-	13.53	-	12.79	-	15.29	-	19.31	-	0.44
20	1.35	14.39	-	17.06	-	22.2	-	15.39	b	21.69	b	28.75	b	0.63
30	1.98	16.28	b	22.76	-	28.75	-	16.37	b	23.16	b	29.92	b	0.77
40	2.49	17.75	b	23.67	b	30.67	b	17.24	sl	24.23	b	31.02	b	0.89
50	3.01	18.18	sl	24.12	b	31.46	b	18.09	sl	25.17	b	32.18	b	0.99
60	3.59	18.96	sl	24.99	b	32.45	b	19.13	sl	26.12	b	33.16	b	1.09
70	4.23	19.67	sl	25.51	b	33.08	b	19.7	sl	27.13	b	34.15	b	1.18
80	4.82	20.39	sl	26.28	b	34.09	b	20.53	sl	27.95	b	35.26	b	1.26
90	5.28	21.07	sl	26.91	b	35.15	b	21.25	sl	28.32	sw	36.03	b	1.33
100	5.89	21.36	sl	27.72	b	35.91	b	21.66	sw	29.05	sw	36.74	sw.r	1.41
110	6.47	22.36	sw	28.35	sw.r	36.14	b	22.14	sw	29.98	sw	37.17	sw.r	1.48
120	7.13	23.04	sw	29.05	sw.r	36.73	sw.r	22.99	sw	30.67	sw	37.93	sw.r	1.54
130	7.77	23.58	sw	29.47	sw.r	37.46	sw.r	23.39	sw	31.21	sw	38.12	sw.r	1.60
140	8.03	24.06	sw	30.17	sw.r	37.95	sw.r	24.22	sw	32.83	sw	39.02	sw.r	1.66
150	8.59	24.57	sw	30.68	sw.r	38.18	sw.r	24.85	sw	33.07	sw	39.96	sw.r	1.72
160	9.26	25.16	sw	31.2	sw.r	38.93	sw.r	25.29	sw	33.72	sw	40.76	sw.r	1.78
170	9.97	25.57	sw	31.92	sw.r	39.18	sw.r	26.07	sw	34.13	sw	41.23	sw.r	1.83
180	10.13	26.3	sw	32.69	sw.r	40.11	sw.r	26.92	sw	35.07	sw	42.12	sw.r	1.89

Orifice Pressure Drop	P2-P3	P1-P3	Regime	P1-P3	Regime	P1-P3	Regime	P1-P3	Regime	P1-P3	Regime	P1-P3	Regime	Superficial Velocity
mmH2O	empty bed	1 kg, small sphere		1.5 kg small sphere		2 kg, small sphere		1 kg, rice		1.5 kg, rice		2kg, rice		m/s
10	0.7	10.71	-	14.97	-	18.69	-	8.76	-	9.67	-	10.11	-	0.44
20	1.35	15.52	b	19.66	-	23.47	-	14.98	b	17.06	-	20.34	-	0.63
30	1.98	16.72	sl	23.07	b	29.58	b	16.81	b	23.43	-	27.67	-	0.77
40	2.49	17.19	sl	23.97	b	31.33	b	17.75	b	24.21	b	31.82	b	0.89
50	3.01	17.73	sl	24.89	sl	32.37	b	18.21	b	24.97	b	32.73	b	0.99
60	3.59	18.82	sl	25.27	sl	32.88	b	18.86	sl	25.79	b	33.86	b	1.09
70	4.23	19.37	sl	26.33	sl	33.99	b	19.71	sl	26.42	b	34.19	b	1.18
80	4.82	20.3	sl	26.98	sl	34.15	sw.r	20.31	sl	26.96	b	34.99	b	1.26
90	5.28	20.81	sl	27.69	sl	35.46	sw.r	21.22	sl	27.98	b	35.44	b	1.33
100	5.89	21.08	sw	28.07	sw.r	35.93	sw.r	21.96	sl	28.91	sw.r	36.34	sw.r	1.41
110	6.47	21.54	sw	29.15	sw.r	36.23	sw.r	22.11	sw	29.22	sw.r	37.87	sw.r	1.48
120	7.13	22.03	sw	29.94	sw.r	37.06	sw.r	22.64	sw	29.74	sw.r	38.46	sw.r	1.54
130	7.77	22.86	sw	30.62	sw.r	37.46	sw.r	23.03	sw	30.54	sw.r	38.85	sw.r	1.60
140	8.03	23.72	sw	31.33	sw.r	38.64	sw.r	23.87	sw	31.29	sw.r	39.47	sw.r	1.66
150	8.59	24.01	sw	32.45	sw.r	39.28	sw.r	24.23	sw	31.98	sw.r	40.09	sw.r	1.72
160	9.26	24.73	sw	33.03	sw.r	40.17	sw.r	25.19	sw	32.85	sw.r	40.65	sw.r	1.78
170	9.97	25.34	sw	34.18	sw.r	41.88	sw.r	25.67	sw	33.38	sw.r	41.25	sw.r	1.83
180	10.13	26.71	sw	35.21	sw.r	42.34	sw.r	26.29	sw	34.57	sw.r	42.04	sw.r	1.89

Appendix D - Data Collected for Distributor with Backward Twisted Blades

Orifice Pressure Drop	P2-P3	P1-P3	Regime	P1-P3	Regime	P1-P3	Regime	P1-P3	Regime	P1-P3	Regime	P1-P3	Regime	Superficial Velocity
mmH2O	empty bed	1 kg,big sphere		1.5 kg, big sphere		2 kg, big sphere		1 kg, irregular/flat		1.5 kg, irregular/flat		2kg, irregular/flat		m/s
10	1.53	8.42	-	10.55	-	13.53	-	12.79	-	15.29	-	19.31	-	0.44
20	2.85	14.39	-	17.65	-	22.2	-	15.39	b	21.69	b	28.75	b	0.63
30	3.94	16.28	b	22.76	-	28.75	-	16.37	b	23.16	b	29.92	b	0.77
40	4.86	17.75	b	23.67	b	30.67	b	17.24	sl	24.23	b	31.02	b	0.89
50	6.25	18.18	sl	24.12	sl	31.46	b	18.09	sl	25.17	sl	32.18	b	0.99
60	7.19	18.96	sl	24.99	sl	32.45	b	19.13	sl	26.12	sl	33.16	b	1.09
70	8.64	19.67	sl	25.51	sl	33.08	b	19.7	sl	27.13	sl	34.15	b	1.18
80	9.71	20.39	sl	26.28	sl	34.09	b	20.53	sl	27.95	sl	35.26	b	1.26
90	10.72	21.07	sl	26.91	sl	35.15	b	21.25	sl	28.32	sw	36.03	b	1.33
100	11.89	21.36	sl	27.72	sl	35.91	b	21.66	sw	29.05	sw	36.74	sw.r	1.41
110	18.89	22.36	sw	28.35	sw.r	36.14	b	22.14	sw	29.98	sw	37.17	sw.r	1.48
120	14.36	23.04	sw	29.05	sw.r	36.73	sw.r	22.99	sw	30.67	sw	37.93	sw.r	1.54
130	15.25	23.58	sw	29.47	sw.r	37.46	sw.r	23.39	sw	31.21	sw	38.12	sw.r	1.60
140	16.51	24.06	sw	30.17	sw.r	37.95	sw.r	24.22	sw	32.83	sw	39.02	sw.r	1.66
150	17.47	24.57	sw	30.68	sw.r	38.18	sw.r	24.85	sw	33.07	sw	39.96	sw.r	1.72
160	18.71	25.16	sw	31.2	sw.r	38.93	sw.r	25.29	sw	33.72	sw	40.76	sw.r	1.78
170	19.58	25.57	sw	31.92	sw.r	39.18	sw.r	26.07	sw	34.13	sw	41.23	sw.r	1.83
180	20.41	26.3	sw	32.69	sw.r	40.11	sw.r	26.92	sw	35.07	sw	42.12	sw.r	1.89

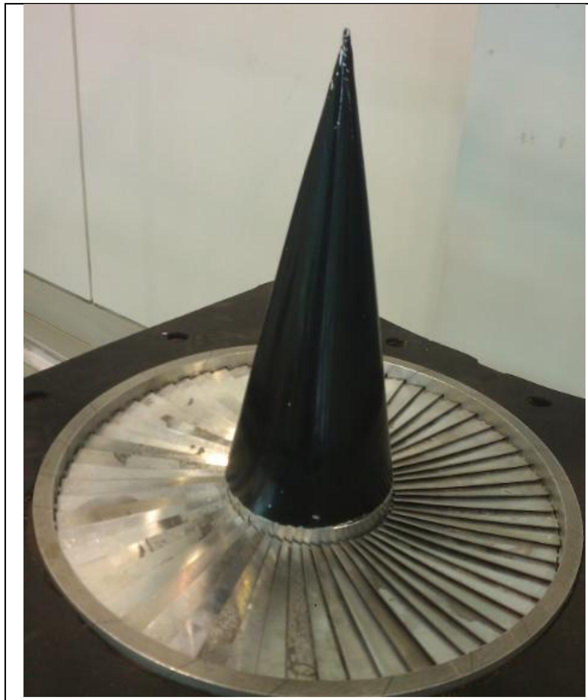
Orifice Pressure Drop	P2-P3	P1-P3	Regime	P1-P3	Regime	P1-P3	Regime	P1-P3	Regime	P1-P3	Regime	P1-P3	Regime	Superficial Velocity
mmH2O	empty bed	1 kg, small sphere		1.5 kg small sphere		2 kg, small sphere		1 kg, rice		1.5 kg, rice		2kg, rice		m/s
10	0.7	10.71	-	14.97	-	18.69	-	8.76	-	9.67	-	10.11	-	0.44
20	1.35	15.52	b	19.66	-	23.47	-	14.98	b	17.06	-	20.34	-	0.63
30	1.98	16.72	sl	23.07	b	29.58	b	16.81	b	23.43	-	27.67	-	0.77
40	2.49	17.19	sl	23.97	b	31.33	b	17.75	b	24.21	b	31.82	b	0.89
50	3.01	17.73	sl	24.89	sl	32.37	b	18.21	b	24.97	b	32.73	b	0.99
60	3.59	18.82	sl	25.27	sl	32.88	b	18.86	sl	25.79	b	33.86	b	1.09
70	4.23	19.37	sl	26.33	sl	33.99	b	19.71	sl	26.42	b	34.19	b	1.18
80	4.82	20.3	sl	26.98	sl	34.15	sw.r	20.31	sl	26.96	b	34.99	b	1.26
90	5.28	20.81	sl	27.69	sl	35.46	sw.r	21.22	sl	27.98	b	35.44	b	1.33
100	5.89	21.08	sw	28.07	sw.r	35.93	sw.r	21.96	sl	28.91	sw.r	36.34	sw.r	1.41
110	6.47	21.54	sw	29.15	sw.r	36.23	sw.r	22.11	sw	29.22	sw.r	37.87	sw.r	1.48
120	7.13	22.03	sw	29.94	sw.r	37.06	sw.r	22.64	sw	29.74	sw.r	38.46	sw.r	1.54
130	7.77	22.86	sw	30.62	sw.r	37.46	sw.r	23.03	sw	30.54	sw.r	38.85	sw.r	1.60
140	8.03	23.72	sw	31.33	sw.r	38.64	sw.r	23.87	sw	31.29	sw.r	39.47	sw.r	1.66
150	8.59	24.01	sw	32.45	sw.r	39.28	sw.r	24.23	sw	31.98	sw.r	40.09	sw.r	1.72
160	9.26	24.73	sw	33.03	sw.r	40.17	sw.r	25.19	sw	32.85	sw.r	40.65	sw.r	1.78
170	9.97	25.34	sw	34.18	sw.r	41.88	sw.r	25.67	sw	33.38	sw.r	41.25	sw.r	1.83
180	10.13	26.71	sw	35.21	sw.r	42.34	sw.r	26.29	sw	34.57	sw.r	42.04	sw.r	1.89

Appendix E - Data Collected for Distributor with Straight Blades

Orifice Pressure Drop	P2-P3	P1-P3	Regime	P1-P3	Regime	P1-P3	Regime	P1-P3	Regime	P1-P3	Regime	P1-P3	Regime	Superficial Velocity
mmH_2O	empty bed	1 kg,big sphere		1.5 kg, big sphere		2 kg, big sphere		1 kg, irregular/flat		1.5 kg, irregular/flat		2kg, irregular/flat		m/s
10	3.69	15.02	-	17.08	-	18.01	-	12.35	-	19.07	-	27.26	-	0.44
20	6.97	20.75	b	25.17	-	31.59	-	19.02	b	27.13	b	34.65	b	0.63
30	9.51	23.87	b	30.75	b	39.62	-	23.04	b	30.82	b	38.39	b	0.77
40	12.13	25.91	b	33.31	b	40.51	b	26.49	sl	33.99	b	41.67	b	0.89
50	14.51	28.73	sl	35.95	b	42.97	b	30.13	sl	36.81	sl	43.73	b	0.99
60	17.21	30.03	sl	37.03	sl	45.57	b	32.09	sl	39.27	sl	46.37	b	1.09
70	19.87	32.15	sw	41.07	sl	49.11	b+sw	34.37	sl	41.78	sl	49.97	b	1.18
80	22.18	35.07	sw	43.15	b+sw	51.23	b+sw	38.25	sl	44.64	sl	51.22	b	1.26
90	24.38	41.23	sw	47.81	b+sw	54.67	b+sw	40.51	sl	47.73	sw	54.94	b	1.33
100	26.49	43.88	sw	50.97	sw.r	58.14	b+sw	43.87	sw	50.87	sw	58.13	sw.r	1.41
110	29.71	46.77	sw	53.51	sw.r	60.47	sw+sw.r	46.02	sw	53.13	sw	60.51	sw.r	1.48
120	31.97	49.16	sw	56.71	sw.r	64.03	sw+sw.r	50.74	sw	56.45	sw	64.15	sw.r	1.54
130	33.23	52.49	sw	59.97	sw.r	67.48	sw+sw.r	52.09	sw	58.77	sw	66.87	sw.r	1.60
140	35.61	54.37	sw	62.33	sw.r	70.29	sw+sw.r	54.37	sw	63.01	sw	69.83	sw.r	1.66
150	37.89	57.26	sw	64.69	sw.r	72.17	sw+sw.r	57.15	sw	64.95	sw	71.45	sw.r	1.72
160	41.53	60.93	sw	68.41	sw.r	75.89	sw+sw.r	60.07	sw	67.33	sw	74.58	sw.r	1.78
170	44.09	64.36	sw	71.51	sw.r	78.91	sw+sw.r	63.48	sw	70.41	sw	77.99	sw.r	1.83
180	46.75	66.79	sw	73.92	sw.r	81.05	sw+sw.r+j	66.85	sw	73.61	sw	80.37	sw.r	1.89

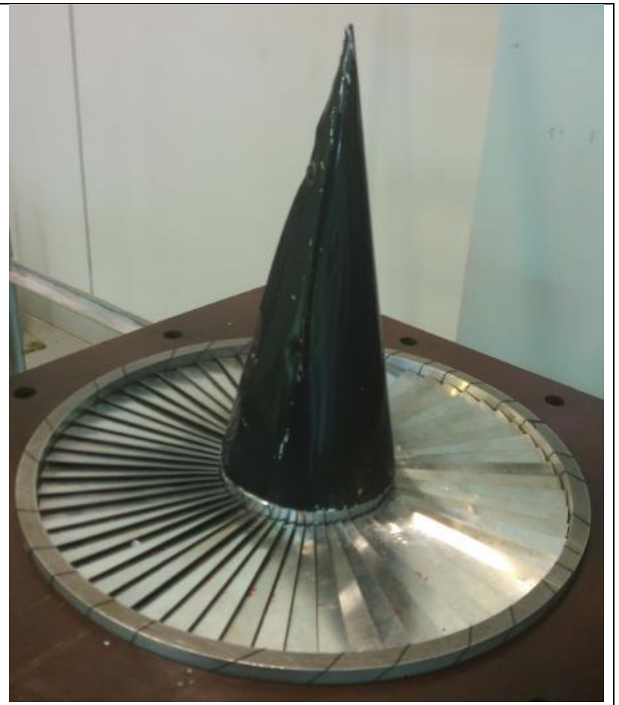
Orifice Pressure Drop	P2-P3	P1-P3	Regime	P1-P3	Regime	P1-P3	Regime	P1-P3	Regime	P1-P3	Regime	P1-P3	Regime	Superficial Velocity
mmH_2O	empty bed	1 kg, small sphere		1.5 kg small sphere		2 kg, small sphere		1 kg, rice		1.5 kg, rice		2kg, rice		m/s
10	3.69	15.05	-	17.05	-	19.27	-	17.37	-	19.35	-	20.21	-	0.44
20	6.97	22.65	b	28.35	-	32.91	-	23.15	b	27.89	-	33.86	-	0.63
30	9.51	24.87	sl	29.51	b	34.27	b	26.12	b	32.91	-	41.75	-	0.77
40	12.13	26.94	sl	33.17	b	38.78	b	27.98	b	35.45	b	42.39	b	0.89
50	14.51	29.86	sl	36.62	sl	43.13	b	30.78	b	38.14	b	45.22	b	0.99
60	17.21	31.27	sl	39.57	sl	47.75	b	32.14	sl	39.59	b	47.56	b	1.09
70	19.87	34.46	sl	41.81	sl	49.21	b	34.64	sl	43.38	b	51.48	b	1.18
80	22.18	37.18	sl	44.21	sl	51.24	sw.r	38.09	sl	45.67	b	53.24	b	1.26
90	24.38	39.69	sl	46.97	sl	53.88	sw.r	43.28	sl	49.98	b	56.81	b	1.33
100	26.49	42.27	sw	49.59	sw.r	56.71	sw.r	45.97	sl	53.11	sw.r	60.45	sw.r	1.41
110	29.71	45.72	sw	52.61	sw.r	59.45	sw.r	48.85	sw	56.03	sw.r	62.83	sw.r	1.48
120	31.97	48.92	sw	55.78	sw.r	62.54	sw.r	51.28	sw	58.71	sw.r	66.52	sw.r	1.54
130	33.23	51.93	sw	59.03	sw.r	65.83	sw.r	54.59	sw	62.03	sw.r	69.74	sw.r	1.60
140	35.61	53.27	sw	61.47	sw.r	66.17	sw.r	56.81	sw	64.47	sw.r	72.86	sw.r	1.66
150	37.89	56.65	sw	64.57	sw.r	71.93	sw.r	59.65	sw	66.58	sw.r	74.31	sw.r	1.72
160	41.53	59.81	sw	68.24	sw.r	76.37	sw.r	63.83	sw	70.73	sw.r	77.59	sw.r	1.78
170	44.09	63.11	sw	71.49	sw.r	79.23	sw.r	66.74	sw	74.09	sw.r	81.26	sw.r	1.83
180	46.75	67.54	sw	73.85	sw.r	80.12	sw.r	68.93	sw	76.15	sw.r	83.54	sw.r	1.89

Appendix F – Pictures of Distributor with Forward Twisted Blades, Backward Twisted Blades, and Straight Blades



(a) Distributor with Forward Twisted Blades

(b) Distributor with Straight Blades



(c) Distributor with Backward Twisted Blades

Figure F1. Distributor with (a) Forward Twisted Blades, (b) Straight Blades, (c) Backward Twisted Blades

Appendix G – Calculation of Superficial Velocity

According to Sreenivasan and Raghavan [3], superficial velocity in ms^{-1} is obtained by dividing the measured air flow rate by the distributor ring area.

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

The flow rate (Q) is obtained from the orifice flow rate, which is represented by:

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

Given:

- Pipe diameter, D = 0.1 m
- Orifice diameter hole, d = 0.062 m
- Coefficient of discharge, C_d = 0.068
- Air Density, ρ_{air} = 1.2 kg/m^3
- Beta ratio, $\beta = \frac{d}{D} = \frac{0.062}{0.1} = 0.62$
- Orifice area, $A = \frac{\pi d^2}{4} = \frac{\pi(0.062)^2}{4} = 0.003019 \text{ m}^2$
- Bed area, A_{bed}

  $= \frac{\pi}{4}$ (Bed Outer Diameter, D_o^2 – Bed Inner Diameter, D_i^2) $= \frac{\pi}{4}(0.3^2 - 0.1^2)$

  = 0.0628 m^2

Thus, superficial velocity becomes

$$V_{sup} = \frac{0.003019 \ x \ 0.668 \ x \ \sqrt{2 \ x \ 9.81 \ x \ \frac{Orifice \ \ Pressure \ \ Difference \ \ ,\Delta P}{1.2}}}{\sqrt{1-(\frac{0.062}{0.1})^4}} \text{ x } \frac{1}{0.0628}$$

Superficial Velocity, $V_{sup} = 0.140656\sqrt{Orifice\ Pressure\ Difference, \Delta P}$