

## Numerical Study of the Plenum Chamber of a Swirling Fluidized Bed

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### *Abstract:*

A numerical investigation of the complex flow dynamics in the three-inlet plenum chamber of a swirling fluidized bed is presented. The study focuses on the influence of different geometries of flow modifying center-bodies in the plenum on the flow uniformity and plenum pressure drop, so as to arrive at an optimum choice of the hub. Flow uniformity is assessed from the standard deviation of the velocities at the exit plane of the plenum. Ten different hub geometries, in the shape of cylinder, cone, conical frustum or a combination of these are considered in the study. From the simulation results it is seen that, from the point of view of pressure drop, the best hub geometry is the full-length cylinder. For flow uniformity, the best results are got for a half-length inverted conical hub.

*Keywords: Swirling fluidized bed; Choice of hub; Uniformity of flow; Numerical simulation*

### **1. Introduction**

A great many industrial processes involve contact and interaction between solids and fluids (i.e. gases or liquids). Examples include combustion, gasification of solid fuels, shales or solid wastes, drying of particles, calcining, particle heating, regenerative heat exchange, oxidation or reduction of ores, metal surface treatment and catalytic and thermal cracking [1-2]. A common way to perform such processes is through fluidization.

The swirling fluidized bed is an outcome of studies carried out in order to overcome the disadvantages of the conventional fluidized beds [3-4]. The system featuring the inclined injection of gas through the distributor blades is investigated in the present work. The distributor is made of a number of blades that are truncated sectors of a circle. The blades are arranged at an angle to the horizontal.

The section of a fluidized bed below the distributor plate is called the plenum chamber. This section plays a vital role in

distributing the fluid before it enters the distributor. The quality of distribution affects the performance of the fluidized bed [5-6]. Because of some interesting findings that will be further discussed in the next section, the plenum chamber is now likely to attract more interest; thus, a revival in research on the plenum of the fluidization unit is due.

The flow in the plenum of the swirling fluidized bed is different from and more complex than the situations studied earlier. To the best knowledge of the author, no work has been done hitherto specifically on this case. Therefore the primary objective of the present study is to design a plenum chamber that is expected to lead to optimum performance characteristics of the swirling fluidized bed. This design will focus on the influence of different geometries of flow modifying center-bodies in the plenum on the flow uniformity and plenum pressure drop, so as to arrive at an optimum choice of the hub.

## 2. Methodology

Based on results in [7], a detailed numerical study of the complex flow dynamics in the three-inlet plenum chamber of a swirling fluidized bed as demonstrated in Fig. 1 was carried out. The tangential inlet pipes were of equal dimensions and arranged at constant angular distance around the chamber periphery. Two orthogonal diameters D1 and D2 were chosen to represent the velocity profile at the exit plane of the plenum chamber. The CFD code FLUENT had been used to analyze the flow model.

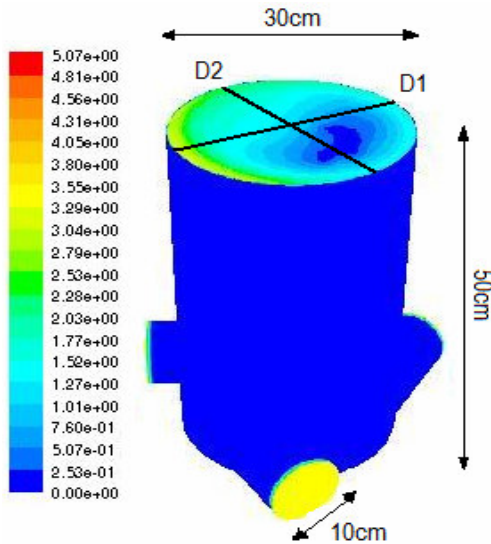


Fig. 1: Air volume domain showing two orthogonal diameters D1 and D2. Velocity contour at the exit plane is exhibited.

Simulations were performed using the finite volume method. Steady-state segregated implicit solver and Reynolds-Averaged Navier-Stokes (RANS) Equations Models, RNG  $\kappa$ - $\epsilon$  model with standard wall treatment were applied to simulate the turbulence flow in the chamber. A standard discretisation scheme was used for the continuity equation while a first-order upwind scheme was used for both the turbulence kinetic energy equation and the

turbulence dissipation rate equation. To reduce numerical diffusion, a second-order upwind scheme was selected for the discretisation of the momentum equations. The SIMPLE algorithm was then applied to solve the pressure-velocity coupling algorithms.

### 2.1 Governing Equations

For the simulation purpose, the following 3-D equations in cylindrical coordinate form have been solved numerically for a Newtonian, incompressible fluid:

Continuity Equation

$$\frac{1}{r} \frac{\partial(rV_r)}{\partial r} + \frac{1}{r} \frac{\partial V_\theta}{\partial \theta} + \frac{\partial V_z}{\partial z} = 0 \quad (1)$$

Conservation of Momentum Equations

$$V_r \frac{\partial V_r}{\partial r} + \frac{V_\theta}{r} \frac{\partial V_r}{\partial \theta} - \frac{V_\theta^2}{r} + V_z \frac{\partial V_r}{\partial z} = -\frac{1}{\rho} \frac{\partial P}{\partial r} + \nu \left\{ \frac{\partial}{\partial r} \left( \frac{1}{r} \frac{\partial}{\partial r} [rV_r] \right) + \frac{1}{r^2} \frac{\partial^2 V_r}{\partial \theta^2} - \frac{2}{r^2} \frac{\partial V_\theta}{\partial \theta} + \frac{\partial^2 V_r}{\partial z^2} \right\} \quad (2)$$

$$V_r \frac{\partial V_\theta}{\partial r} + \frac{V_\theta}{r} \frac{\partial V_\theta}{\partial \theta} + \frac{V_r V_\theta}{r} + V_z \frac{\partial V_\theta}{\partial z} = -\frac{1}{\rho} \frac{\partial P}{\partial \theta} + \nu \left\{ \frac{\partial}{\partial r} \left( \frac{1}{r} \frac{\partial}{\partial r} [rV_r] \right) + \frac{1}{r^2} \frac{\partial^2 V_r}{\partial \theta^2} - \frac{2}{r^2} \frac{\partial V_\theta}{\partial \theta} + \frac{\partial^2 V_r}{\partial z^2} \right\} \quad (3)$$

$$V_r \frac{\partial V_z}{\partial r} + \frac{V_\theta}{r} \frac{\partial V_z}{\partial \theta} + V_z \frac{\partial V_z}{\partial z} = -\frac{1}{\rho} \frac{\partial P}{\partial z} + \nu \left\{ \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial V_z}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 V_z}{\partial \theta^2} + \frac{\partial^2 V_z}{\partial z^2} \right\} \quad (4)$$

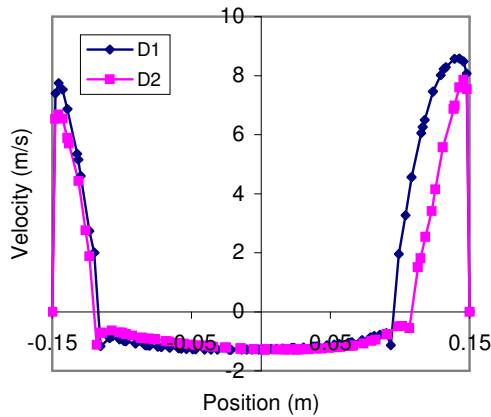
### 2.2 Boundary Conditions

The air inlet was modeled as a velocity inlet maintaining uniform flow rate of  $0.07854 \text{ m}^3/\text{s}$  (velocity of 10 m/s for each inlet). The air outlet was modeled as a pressure outlet of 1.01325 bar (atmospheric pressure). No slip wall conditions were applied. Air has been taken as the fluid domain, while the hub taken as a solid medium.

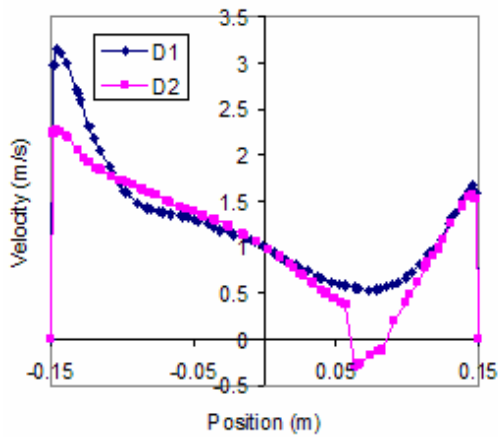
### 3. Results and Discussions

Citing from [7], Fig. 2 (a) yields highly non-uniform velocity profile at the plenum exit when applying a single tangential air inlet into the plenum. High peak in velocity occurs near the circumference of the chamber. Unwanted backflow (negative velocity) appears in a wide region at the center.

Introducing three tangential inlets into the chamber has been proved to accommodate more uniformity [7] as presented in Fig. 2 (b). The backflow also has been greatly reduced.



(a)



(b)

Fig. 2: Velocity on D1 and D2 on the outlet plane (a) single inlet (b) three inlets.

#### 3.1 Hub Designs

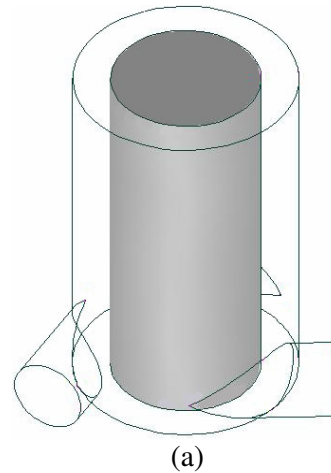
Implanting a hub at the center of the plenum chamber certainly is a great idea due to the annular blade shape of the distributor.

This is to reduce or avoid airflow in plenum center where there is no distributor air gap as well as to eliminate the air backflow in that region.

Previous study [7] has proved that the introduction of a full-length cylindrical hub in the center of the three-inlet plenum yields good uniformity in the velocity profile at the distributor along the radial and tangential direction as well as low total pressure drop.

In the present work, further simulations were carried out considering 10 different geometries of flow modifying center-bodies in the plenum (including the cylindrical hub mentioned above) to arrive at an optimum design for the plenum chamber. The models stick to three tangential air inlets into the chamber.

Fig. 3 shows the three air inlets into the 30 cm diameter plenum chamber with a 20 cm diameter cylindrical hub at the center. The configuration is chosen so that the hub will cover the entire inner diameter of the annular blades, where there is no air gap. This hub design is modeled as model a in Fig. 4. It also shows 9 other hub designs for the same 3-inlets chamber with the same dimensions as model a.



(a)

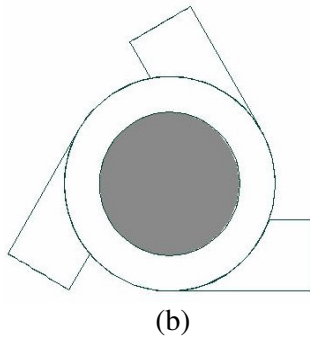


Fig. 3: Three-inlets chamber with a full-length cylindrical hub at the center (a) isometric view (b) plane view.

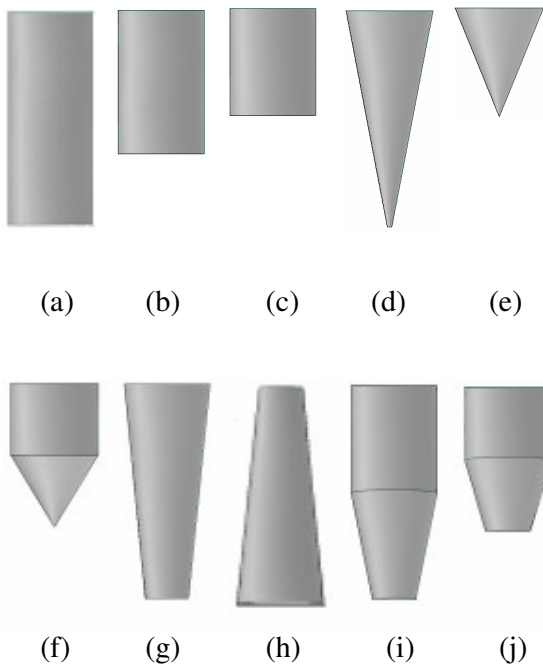


Fig. 4: Various hub designs (model a-i).

### 3.1.1 Pressure Drop

The total pressure drop across the chamber for each model as extracted from the numerical results is tabulated in the following Table 1.

Table 1. The total pressure drops in the plenum chamber for various hub designs.

| Model | Length Type   | Pressure Drop (Pa) |
|-------|---------------|--------------------|
| a     | Full cylinder | 6.57               |

|   |                           |       |
|---|---------------------------|-------|
| b | 2/3 cylinder              | 7.76  |
| c | 1/2 cylinder              | 8.61  |
| d | Full cone                 | 8.34  |
| e | 1/2 cone                  | 9.3   |
| f | 1/3 cylinder, 1/3 cone    | 8.89  |
| g | Full Inverted frustum     | 7.84  |
| h | Full Upright frustum      | 10.25 |
| i | 1/2 cylinder, 1/2 frustum | 6.91  |
| j | 1/3 cylinder, 1/3 frustum | 7.97  |

From the point of view of pressure drop, the best hub geometry is the full-length cylinder.

### 3.1.2 Statistical Analysis

A statistical analysis was conducted in order to provide additional criteria in deciding the geometry of hub to be chosen. The standard deviation of velocity magnitude at the exit plane of the plenum chamber for 10 models was demonstrated in the Table 2. Low standard deviation yields high uniformity.

Table 2. The standard deviation for velocity on the exit plane of the plenum chamber.

| Model | Length Type               | Standard Deviation (m/s) |
|-------|---------------------------|--------------------------|
| a     | Full cylinder             | 1.2                      |
| b     | 2/3 cylinder              | 1.198                    |
| c     | 1/2 cylinder              | 1.134                    |
| d     | Full cone                 | 1.197                    |
| e     | 1/2 cone                  | 1.018                    |
| f     | 1/3 cylinder, 1/3 cone    | 1.041                    |
| g     | Full Inverted frustum     | 1.113                    |
| h     | Full Upright frustum      | 1.766                    |
| i     | 1/2 cylinder, 1/2 frustum | 1.118                    |
| j     | 1/3 cylinder, 1/3 frustum | 1.123                    |

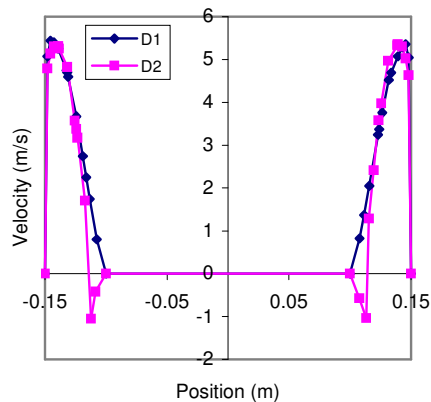
For flow uniformity (low in standard deviation), the best results are got for a half-length inverted conical hub.

Analyzing both pressure drop across the chamber and the standard deviation for

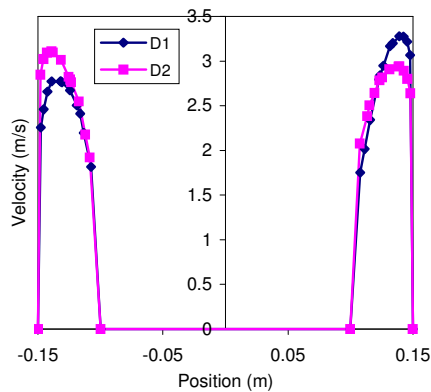
velocity at the outer plane, the model i with a 1/2 cylinder-1/2 frustum hub in the center of the three-inlets plenum is chosen for further consideration. This design provides low pressure drop as well as low standard deviation of velocity which implies high uniformity.

### 3.2 Multiple inlets

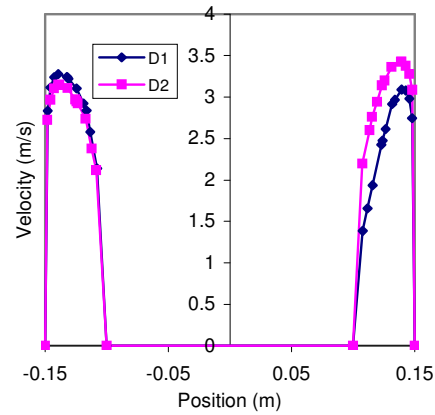
Although three-inlet plenum has been shown in [7] to accommodate the desired characteristics, more simulations were conducted for 2 and 4 inlets to investigate if the pattern is still relevant for the chosen hub.



(a)



(b)



(c)

Fig. 3: Velocity profile on the outlet plane of the plenum with hub design as in model i (a) 2 air inlets (b) 3 air inlets (c) 4 air inlets.

Fig. 4(a-c) presents the velocity profile on the chamber outlet plane for 2, 3 and 4 tangential air inlets. The design was based on the compromise between desired performance characteristic and the unit simplicity. As model with 4 air inlets did not yield much improvement, 3-inlets model i remains the optimum design chosen.

## 4. Conclusion

A numerical investigation of the complex flow dynamics in the three-inlet plenum chamber of a swirling fluidized bed has been carried out. The study focuses on the influence of different geometries of flow modifying center-bodies in the plenum on the flow uniformity and plenum pressure drop, so as to arrive at an optimum choice of the hub. Flow uniformity is assessed from the standard deviation of the velocities at the exit plane of the plenum. Ten different hub geometries, in the shape of cylinder, cone, conical frustum or a combination of these are considered in the study. From the simulation results it is seen that, from the point of view of pressure drop, the best hub geometry is the full-length cylinder. For flow uniformity, the best results are got for a half-length inverted conical hub. However a 1/2 cylinder-1/2 frustum hub in the center of the three-inlet plenum has been chosen as the final design. This design

provides low pressure drop as well as low standard deviation of velocity which implies high uniformity.

### Nomenclature

|                      |                                      |
|----------------------|--------------------------------------|
| $P$                  | <i>pressure</i>                      |
| $\rho$               | <i>density</i>                       |
| $\nu$                | <i>kinematics viscosity</i>          |
| $r, \theta, z$       | <i>cylindrical polar coordinates</i> |
| $V$                  | <i>velocity</i>                      |
| $V_r, V_\theta, V_z$ | <i>component of velocity vector</i>  |

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