CFD Letters www.cfdl.issres.net Vol. 1 (2) – December 2009

Statistical Analysis on the Design of Flow Modifying Centre-Bodies in a Plenum Chamber

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Received: 26/07/2009 – Revised 26/07/2009 – Accepted 14/08/2009

Abstract

The primary objective of this study is to numerically investigate the influence of various geometries of flow modifying centre-bodies on the aerodynamics of flow in the plenum chamber of a swirling fluidized bed. Ten different hub geometries, in the shape of cylinder, cone, conical frustum or a combination of these are considered in the study. Two performance characteristics of interest are flow uniformity at the exit plane of the plenum chamber and the total pressure drop across the plenum. The homogeneity of airflow was assessed from a statistical analysis conducted. From the results, it is evident that the introduction of a full-length cylindrical hub at the centre of the plenum chamber offers a balance in the required performance characteristics.

Keywords: Swirling fluidized be; hub; uniformity of flow; numerical simulation; statistical analysis.

1. Introduction

A swirling fluidized bed consists of an annular distributor made of a number of blades arranged at an angle to the horizontal [1]. The tangential component of air leaving the distributor provides swirl motion and thus enhances the mixing capacity in the bed column [2, 3].

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 [4, 5]. The flow in the plenum of a swirling fluidized bed is different from and more complex than the situations studied in other systems [6, 7].

Previous studies [8-11] were conducted in order to reveal how various features such as inlet pipe arrangements, multiple inlets for gases and consideration of different geometries of flow modifying centre-bodies in the plenum chamber may be chosen so as to arrive at an optimum design for the plenum chamber. A few numerical approaches have been taken into account.

Therefore, the present work is an extended study of [8] to numerically determine the influence of varying the hubs in the plenum chamber. To that end, ten hub designs will again be considered: cylinder, cone, conical frustum and their combinations. In the current work, flow homogeneity is assessed from an expanded statistical analysis on the air velocities upstream of the distributor, for the more recently chosen fifty-percent radially offset inlet pipe [11] into the plenum.

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2. Methodology

Figure 1 shows the schematic diagram of the numerical model. The plenum chamber however, is actually of 50 cm height. The extension of 50 cm in height of the numerical domain is necessary to prevent the occurrence of excessive reversed flow at the outlet [12]. The geometries were generated in GAMBIT environment. The CFD code FLUENT had been used to solve the 3-D governing equations for steady state fluid flow (equations 1 to 4). A validated [10] numerical approach has been applied. The Reynolds-Averaged Navier-Stokes (RANS) Equations Model and Reynolds Stress Model (RSM) with standard wall treatment were applied to simulate the turbulent flow in the chamber. A standard discretisation scheme was used for the continuity equation. To reduce numerical diffusion, a second-order upwind scheme was selected for the discretisation of the momentum equations, turbulent kinetic energy equation and the turbulence dissipation rate equation. The SIMPLE algorithm was then applied to solve the pressure-velocity coupling algorithms. A grid independent mesh interval of 7 mm [10] for the whole domain has been chosen (1 003 092 mesh volumes). Typical computation times of one day were consumed for each case (PC used was Intel Core 2 Duo 2.33GHz, 3.00 GB RAM).

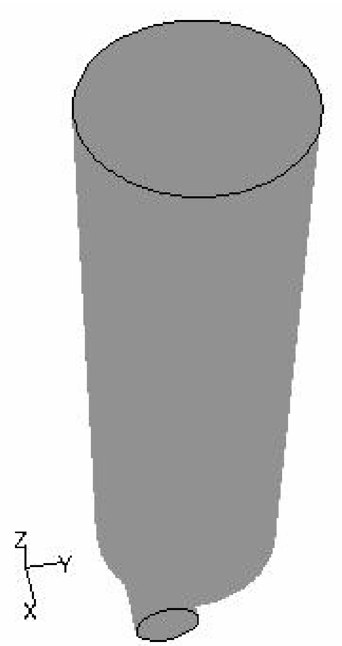


Figure (1) Numerical domain

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

$$\frac{1}{r}\frac{\partial(rv_r)}{\partial r}+\frac{1}{r}\frac{\partial v_\phi}{\partial \phi}+\frac{\partial v_z}{\partial z}=0 \qquad (1)$$

Conservation of Momentum Equations

$$v_r\frac{\partial v_r}{\partial r}+\frac{v_\phi}{r}\frac{\partial v_r}{\partial \phi}-\frac{v_\phi^2}{r}+v_z\frac{\partial v_r}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial r}+\frac{\mu}{\rho}\left\{\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial}{\partial r}[rv_r]\right)+\frac{1}{r^2}\frac{\partial^2 v_r}{\partial \phi^2}-\frac{2}{r^2}\frac{\partial v_\phi}{\partial \phi}+\frac{\partial^2 v_r}{\partial z^2}\right\} \qquad (2)$$

$$v_r \frac{\partial v_\phi}{\partial r} + \frac{v_\phi}{r}\frac{\partial v_\phi}{\partial \phi} + \frac{v_r v_\phi}{r} + v_z \frac{\partial v_\phi}{\partial z} = -\frac{1}{r\rho}\frac{\partial p}{\partial \phi} + \frac{\mu}{\rho}\left\{\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial}{\partial r}\left[r v_\phi\right]\right) + \frac{1}{r^2}\frac{\partial^2 v_\phi}{\partial \phi^2} + \frac{2}{r^2}\frac{\partial v_r}{\partial \phi} + \frac{\partial^2 v_\phi}{\partial z^2}\right\} \quad (3)$$

$$v_r \frac{\partial v_z}{\partial r} + \frac{v\phi}{r}\frac{\partial v_z}{\partial \phi} + v_z \frac{\partial v_z}{\partial z} = -\frac{1}{\rho}\frac{\partial p}{\partial z} + \frac{\mu}{\rho}\left\{\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial v_z}{\partial r}\right) + \frac{1}{r^2}\frac{\partial^2 v_z}{\partial \theta^2} + \frac{\partial^2 v_z}{\partial z^2}\right\} \quad (4)$$

2.2. Boundary conditions

The inlet air flow was modeled at a uniform velocity of 12 m/s, while the outlet was modeled at a constant atmospheric pressure of 1.01325bar. Also, non-slip wall conditions were applied. Air has been taken as the fluid domain, while the hub is taken as a solid medium.

2.3. Statistical parameters

A statistical analysis was conducted in the relative design of the hubs. Four statistical parameters, mean (the first moment about zero), standard deviation (positive square root of the second central moment, variance), skewness (the normalized third central moment) and kurtosis (the normalized fourth central moment minus three), are mathematically defined in equations 5 to 9.

While a particular moment gives little information about a distribution, the whole set of moments will ordinarily determine the distribution satisfactorily. For this reason, this approach is used in the present study.

The following are the general equations for each statistical parameter in consideration [13]:

Mean velocity:

$$v_{mean} = \frac{1}{N}\sum_{1}^{N} v_i \quad (5)$$

Standard deviation of velocity:

$$v_{rms} = \left[\frac{1}{N-1}\sum_{1}^{N}\left(v_i - v_{mean}\right)\right]^{0.5} \quad (6)$$

Skewness:

$$S = \sum_{1}^{N}\frac{\left(v_i - v_{mean}\right)^3}{N \cdot \sigma^3} \quad (7)$$

Kurtosis:

$$K = \sum_{1}^{N}\frac{\left(v_i - v_{mean}\right)^4}{N \cdot \sigma^4} \quad (8)$$

where the variance σ is defined as:

$$\sigma = \left[\sum_{1}^{N}\frac{\left(v_i - v_{mean}\right)^2}{N-1}\right]^{0.5} \quad (9)$$

3. Results and discussion

Implanting flow modifying centre-bodies in the plenum chamber certainly is a plausible idea due to the annular blade shape of the distributor [1]. This is to reduce or avoid airflow in the plenum center where there is no distributor air gap as well as to eliminate the air backflow in that region.

One of the hub designs is a full (height similar with the plenum) cylindrical hub at the center of the plenum chamber. Figure 2 demonstrates how a 20 cm diameter cylindrical hub is implanted at the center of a plenum chamber of 30 cm diameter. This configuration is chosen so that the hub will cover the entire inner diameter of the annular blades, where there is no air gap.

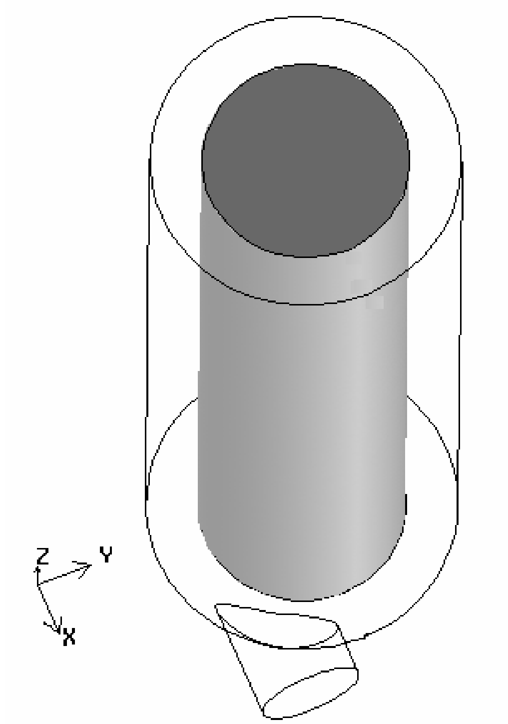
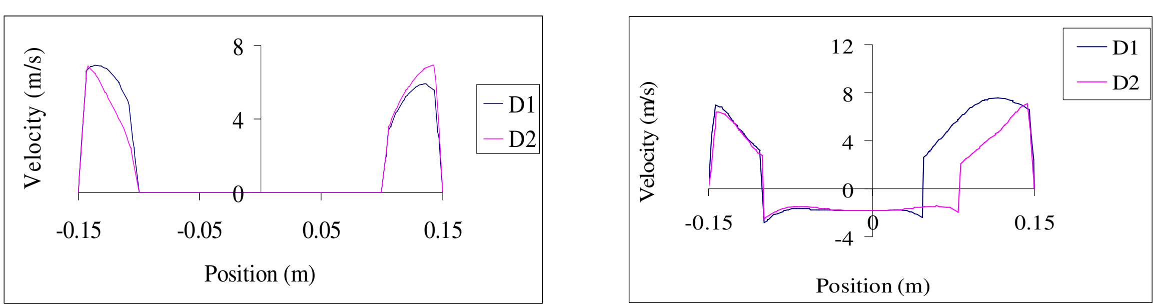


Figure (2) Cylindrical hub at the center of the plenum chamber

The presentation of the simulation results in figures 3a and b yield improved flow characteristics in the region of interest, i.e., the plenum exit plane, with the introduction of a cylindrical hub at the centre of the column. D1 and D2 are two orthogonal diameters on the plenum exit plane as shown in figure 4. In this design, airflow is restricted within an annular path between two cylinders. As a result, the desired high uniformity swirling airflow upstream of the distributor is evident in the flow vectors, figure 5.

Figure 3a ascertains the elimination of backflow (negative velocity) near the centre of the column. This improvement is predicted to reduce both non-uniformity and pressure losses in the plenum, as verified by results tabulated in table 1.



(a) (b)

Figure (3) Velocity profile on D1 anD2 for (a) plenum with hub (b) empty plenum

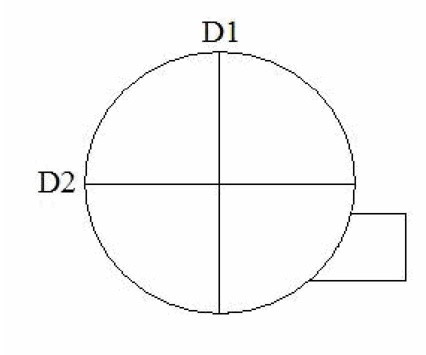


Figure (4) Two orthogonal diameters on the plenum exit plane

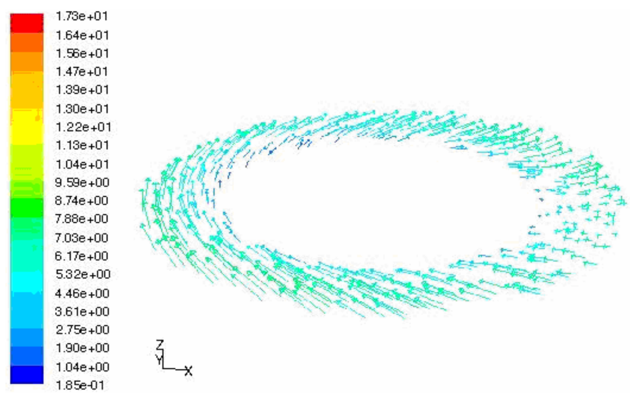


Figure (5) Vector of velocity magnitude (m/s) for plenum with cylindrical hub implanted

In terms of velocity homogeneity on the plenum outlet surface, the design incorporating a cylindrical centre-body shows superior statistical parameters: mean, standard deviation and skewness. High mean velocity and low standard deviation of velocities are straight forwardly beneficial. For skewness, although the empty plenum chamber exhibits a distribution closer to the normal distribution (skewness nearer to zero), it has positive skewness coefficient, which means it contains only a few high values. The plenum chamber with a hub on the other hand, has a negative skewness coefficient and implies that it is dominated by high velocities. However, the latter design consists of higher variance due to infrequent extreme deviations (high 'peakedness' of the probability distribution), owing to high kurtosis.

The pressure drop across the plenum with a cylindrical hub implanted at the centre was found to be lower than the case without it. Although it was expected that the hub should introduce more obstruction to the airflow as it goes through the plenum chamber, the confined annulus path (a relatively shorter travel path) and the elimination of separation losses at the column center give the former set up an advantage with respect to pressure loss.

TABLE 1: STATISTICAL PARAMETERS AND OVERALL PRESSURE DROP FOR PLENUM WITH AND WITHOUT CYLINDRICAL HUB IMPLANTED

Hub	Mean (m/s)	Standard deviation (m/s)	Skewness	Kurtosis	Pressure drop (Pa)
Cylindrical	5.21	1.72	-1.05	0.30	2.62
None	4.15	2.03	0.109	-1.460	16.42

In the current work, the cylindrical hub design is modeled as (a) (figure 6). It also shows nine other hub designs with the exact dimensions proportion as model **a**. As it has been proved that the introduction of a full-length cylindrical hub in the center of the plenum yields good uniformity in the velocity profile at the distributor as well as maintaining low total pressure drop, further simulations were carried out considering nine other geometries of flow modifying center-bodies in the plenum (b-j) to arrive at an optimum design for the plenum chamber. The results are elaborated in the following sections.

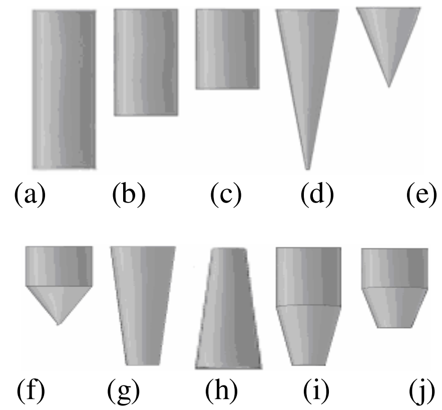


Figure (6) Various hub designs (model (a)-(j))

3.1. Pressure Drop

The total pressure drops across the chamber for ten different geometries of flow modifying center-bodies in the plenum (a-j), as extracted from the numerical results, are set out in the following table 2. Because of the discrete nature of changes in the geometry of the hubs, it is impossible to specify a definite trend of the obtained results above. However a few remarkable patterns could be highlighted.

For instance, among the three models (a, g and h), the model **a** with a full cylindrical hub provides a straight annular path for airflow, hence the least loss in pressure due to low flow separation. In models g and h, the slanted hubs promote convergence and divergence of the airflow respectively. Generation of stream wise vorticity or secondary motion makes the flow structure complicated and causes larger pressure losses in the plenum chamber when compared to straight ducts. In fact, the divergence of the airflow in model h causes it to be the worst design (compared to the other nine models) in terms of pressure losses, while (a) turned out to be the best choice.

TABLE 2: THE TOTAL PRESSURE DROPS IN THE PLENUM CHAMBER FOR VARIOUS HUB DESIGNS.

Model	Length Type	Pressure Drop (Pa)
a	Full cylinder	2.62
b	2/3 cylinder	13.66
c	1/2 cylinder	14.89
d	Full cone	7.66
e	1/2 cone	8.23
f	1/3 cylinder, 1/3 cone	5.85
g	Full Inverted frustum	15.39
h	Full Upright frustum	30.10
i	1/2 cylinder, 1/2 frustum	18.15
j	1/3 cylinder, 1/3 frustum	9.17

Models (a, b and c) consist of three different heights of the cylindrical hub introduced at the centre of the chamber. Reducing the height increases the overall pressure drop across the plenum. A secondary airflow, which has lost most of its swirling velocity, is expected at the centre region of the chambers with hub models (b) and (c). A shorter hub will provide more space for secondary flow, and consequently causes larger loss in pressure. Similar patterns apply for conical hubs (models d and e). These mixed patterns lead to the combination of cylinder-cone and cylinder frustum hubs (model f, i and j).

3.1. Homogeneity of velocity distribution

A statistical analysis was conducted in order to provide additional criteria in deciding the geometry of the hub to be chosen. Once again four statistical parameters are calculated for velocity magnitude at the exit plane of the plenum chamber: mean, standard deviation, skewness and kurtosis. The outcomes for ten models (a-j) are shown in the table 3.

TABLE 3: THE STATISTICAL PARAMETERS FOR VELOCITY ON THE EXIT PLANE OF THE PLENUM CHAMBER

Model	Mean (m/s)	Standard Deviation (m/s)	Skewness	Kurtosis
a	5.21	1.72	-1.047	0.295
b	5.66	1.80	-1.104	0.800
c	5.93	1.85	-1.075	0.643
d	5.91	1.77	-1.083	0.574
e	5.74	1.73	-0.739	0.210
f	5.93	1.99	-0.853	-0.119
g	6.46	1.84	-0.812	0.333
h	5.14	2.05	-0.151	-1.047
i	6.44	2.00	-1.168	0.766
j	5.82	1.89	-0.836	-0.041

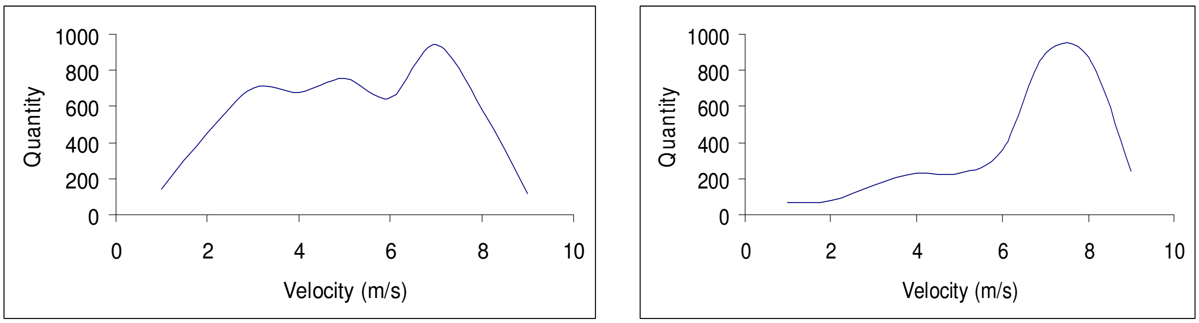
As discussed earlier, mean is the least weighted statistical parameter in the current analysis. It is interesting to note that the full inverted frustum, model g**,** accommodates the highest mean velocity at the plenum exit which is favored, while the full upright frustum model h comes out with the lowest.

This is followed by the skewness. All hub designs have negative skewness coefficient (mass distribution concentrated on the right side), which means they contain only a few relatively low velocities. The full upright frustum model h shows skewness closest to zero, demonstrating its proximity to the normal distribution, which is preferable as exhibited in figure 7a. The half-cylinder, half frustum model i on the other hand, has the largest negative coefficient, refering to its most asymmetrical velocity distribution figure 7(b).

Low kurtosis indicates frequent modestly-sized deviations. Full upright frustum model h therefore has the best desirable flatness factor (figure 7a) due to its lowest kurtosis. In contrast, the one-third-cylindrical hub (model b) provides most variance due to infrequent extreme deviations, as it has the greatest kurtosis. This is followed by the half-cylinder, half-frustum model (i) figure 7(b).

Standard deviation is the square root of variance in a probability distribution. Consequently, it denotes the variation to the mean value. Low in standard deviation is needed as it implies high uniformity in velocity. Therefore in the present study, the full cylindrical hub model (a) offers the best velocity homogeneity, while the full upright frustum model (h) is the worst as a much larger centre region is available on the exit plane for the reverse flow to occur.

Analyzing both pressure drops across the chamber and the statistical analysis for velocity at the outer plane, the model (a) with a full cylindrical hub in the center of the plenum is chosen for further consideration. This design combines a reasonably low pressure drop and a fairly high uniformity.



(a) (b)

Figure (7) Probability distribution for (a) model h (b) model i

4. Conclusion

The main objective of this study, which is to investigate the influence of various geometries of hubs to the flow structure in the plenum chamber, has been achieved. Ten different hub geometries have been considered. A statistical analysis has been conducted to assess the homogeneity of airflow on the plenum outlet plane. From the numerical results, it is evident that the introduction of a full-length cylindrical hub at the centre of the plenum chamber accommodates high uniformity of velocities on the plane of interest while maintaining low pressure drop across the chamber. Therefore, this centre-body design in the plenum chamber has been chosen as it is expected to lead to optimum performance characteristics of a swirling fluidized bed.

Acknowledgement

The first author would like to acknowledge the sponsorship from University Tun Hussein Onn Malaysia (UTHM). Also thanks to staff of Department of Mechanical and Manufacturing Engineering of UTHM, especially Prof. Abas Abdul Wahab, for every help and encouragement. The authors also thank Universiti Teknologi Petronas for the assistance offered by Prof. Vijay R. Raghavan and for their continued support.

Nomenclature

p	pressure
ρ	density
μ	dynamic viscosity
r,ϕ,z	cylindrical polar coordinates
x,y,z	cartesian coordinates
v	velocity
v_r, v_ϕ, v_Z	component of velocity vector
N	number of sample

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