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Numerical Investigation of Airflow in a Swirling Fluidized Bed

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ABSTRACT

A numerical investigation via commercial Computational Fluid Dynamic (CFD) package, FLUENT, was carried out to investigate the aerodynamic characteristics of air flow in a Swirling Fluidized Bed (SFB). The study focused on the distributor blade configurations whereby the effect of number of blades and blade inclination in radial plane were investigated. Twelve configurations were simulated at 30, 45 and 60 blades for four radial inclinations, 0, 10, 13.5 and 15°. Two criterions were taken as performance characteristics to evaluate each configuration namely the uniformity of tangential velocity distribution and pressure drop. High uniformity at the distributor outlet will ensure uniform solid-gas contact in the actual system while low pressure drop is vital to minimize power consumption in the system. From the results, it was evident that the 30 blades with 10E radial inclination of distributor blade in plenum chamber offer the best configuration for actual application.

Key words: Aerodynamic, tangential velocity, radial velocity, axial velocity, uniformity of flow

INTRODUCTION

Fluidization is the operation by which solid particles are suspended in a gas or liquid. This method of contacting between solid and fluid has some unusual characteristics and fluidization engineering puts them to good use (Kunii and Levenspiel, 1991). The basic mechanism of a fluidized bed can be simply seen as fluid percolation through particle interstices via a distributor, in which particles begin to exhibit fluid like characteristic upon experiencing sufficient drag force from the fluid. A large number of industrial processes use the fluidization technique in their daily operations, namely drying of particles, gasification of solid fuels by, combustion, particle heating, oxidation, metal surface treatments and catalytic and thermal cracking (Puranik *et al*., 2012; Arumugam and Ponnusami, 2012; Howard, 1989).

A large number of fluidized bed concepts and configurations are available around the globe and one of the successful variant is the Swirling Fluidized Bed (SFB) and sometimes known as toroidal bed. As the name implies, a SFB imparts swirling motion inside the bed to promote lateral mixing which is highly desired in a fluidized bed. The swirling motion is a result of inclined injection of gas through an annular-blade type distributor, as depicted in Fig. 1.

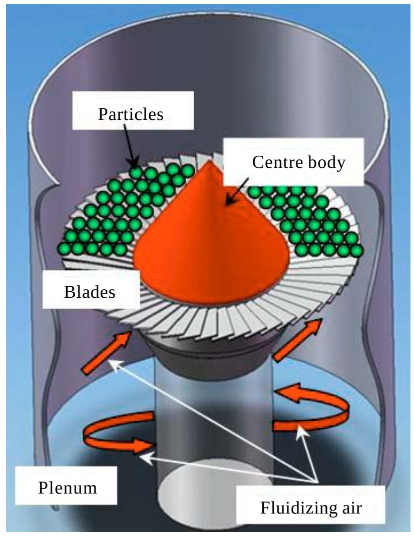

Fig. 1: Basic configuration of a swirling fluidized bed

Though SFB exhibit excellent hydrodynamic characteristics (Shu *et al.*, 2000; Sreenivasan and Raghavan, 2002; Mohideen *et al.*, 2012; Batcha and Raghavan, 2011), the full potential of the bed has not been exploited due to the lack of fundamental understanding on the bed's hydrodynamics. This study aims to investigate the effect of various distributor configurations on fluidizing air introduced inside the bed. As shown in Fig. 1, the distributor is made by an array of blades which are inclined horizontally and radially. The horizontal blade inclination creates swirling-fluidization while radial inclination provides inward momentum to further improve the SFB's hydrodynamics. Since the flow characteristic inside the SFB becomes a complex phenomenon, numerical investigation via CFD studies has been carried out and the findings are reported in this study.

MATERIALS AND METHODS

Investigation of the air flow distribution in a SFB was conducted using commercial CFD software B FLUENT 6.3. The computation domain and grid generation was developed via GAMBIT. Two parameters were varied number of blades (which governs the effective open area of the distributor) and radial inclination angle of the blades to study the effect of air flow distribution in the SFB. The geometry of the distributor blades and their configuration is shown in Fig. 2 and 3 and simulation cases are summarized in Table 1.

Description of the system: The actual SFB system is shown in Fig. 4a. The full scale model was created according to the actual SFB system. The plenum chamber is 525 mm in height while the upper column is 600 mm, both having 300 mm inner diameter. Centre body is a cone with 150 mm height and 200 mm diameter and extends straight to the bottom of the plenum chamber. This results in an annular region for flow with 100 mm hydraulic diameter. The blades are arrayed in anti-clockwise direction with 121 horizontal inclination and each blade is 1 mm thick. Three radial inclination was studied in comparison with conventional annular-blade distributor (01 inclination) which were 101, 13.51 and 151 inclination. The study was limited up to 151 radial inclination

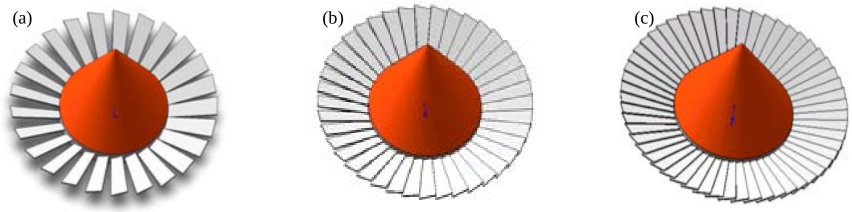

Fig. 2(a-c): SFB distributor with (a) 30, (b) 45 and (c) 60 blades

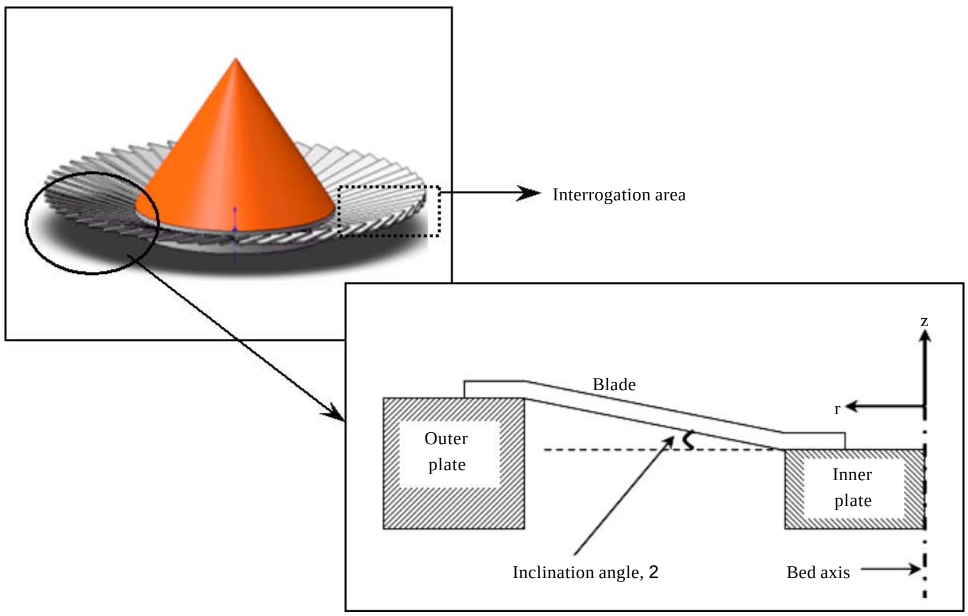

Fig. 3: Radial inclination of the distributor blades: Close-up and interrogation area

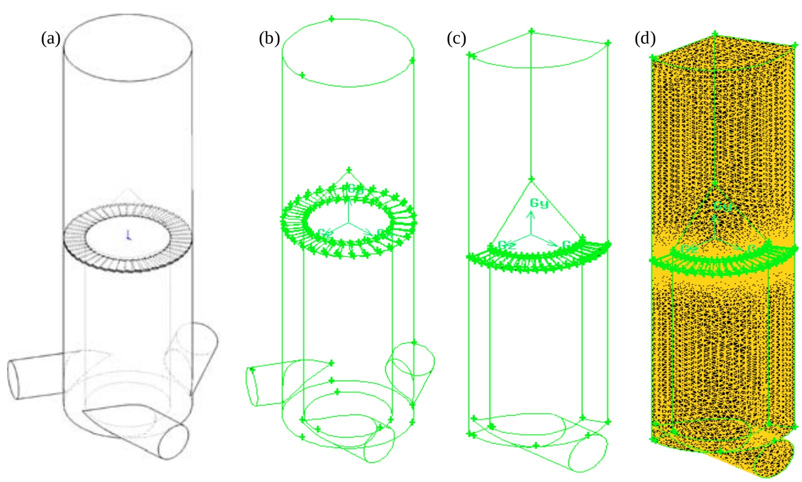

Fig. 4(a-d): (a) Actual SFB system, (b) Computation domain in CFD, (c) Simplified domain and (d) Computation grid

Table 1: SFB distributor configuration

Case	No. of blade	Radial inclination angle of the blades (θ)	Designation
1	30	0°	30-0°
2	30	10°	30-10°
3	30	13.5°	30-13.5°
4	30	15°	30-15°
5	45	0°	45-0°
6	45	10°	45-10°
7	45	13.5°	45-13.5°
8	45	15°	45-15°
9	60	0°	60-10°
10	60	10°	60-10°
11	60	13.5°	60-13.5°
12	60	15°	60-15°

because experimental studies by Sreenivasan and Raghavan (2002) found that any larger angle will result excessive distributor pressure drop and the system will lose its merit.

Numerical model and simplification: Since the geometry of the numerical model is in actual size as in Fig. 4b, large computations are required which is costly. Hence the model was simplified to an axis-symmetric domain with rotational periodic boundary as shown in Fig. 4c with unstructured mesh generated as computation grid (Fig. 4d).

Steady-state segregated implicit solver and Reynolds-Averaged Navier-Stokes (RANS) equation model, RNG k-ε model with standard wall treatment were applied to simulate the turbulence flow in the SFB. 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. Simulation was done using Intel (R) Core(TM) i7 CPU and with 2.80 GHz processor and 12 GB of RAM which runs on Windows 7 (64 bit operating system).

Governing equation: The governing equations for the present study are 3-D momentum and continuity equations in cylindrical coordinate system which were solved for Newtonian, incompressible fluid for in steady flow.

Momentum equation:

(r-direction)

$$\rho\left(v_r\frac{\partial v_r}{\partial r}+\frac{v_\theta\partial v_r}{r\partial\theta}-\frac{{v_\theta}^2}{r}+v_z\frac{\partial v_r}{\partial z}\right)=-\frac{\partial P}{\partial r}+\rho g_r+\mu\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial v_r}{\partial r}\right)-\frac{v_r}{r^2}+\frac{\partial^2 v_r}{r^2\partial\theta^2}-\frac{2\partial v_\theta}{r^2\partial\theta}+\frac{\partial^2 v_r}{\partial z^2}\right]$$

(θ-direction)

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

(z-direction)

$$\rho\left(v_r\frac{\partial v_z}{\partial r}+\frac{v_\theta\partial v_z}{r\partial\theta}+v_z\frac{\partial v_z}{\partial z}\right)=-\frac{\partial P}{\partial z}+\rho g_z+\mu\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial v_z}{\partial r}\right)+\frac{\partial^2 v_z}{r^2\partial\theta^2}+\frac{\partial^2 v_z}{\partial z^2}\right]$$

Continuity equation:

$$\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}\right)=0 \quad (2)$$

RESULTS AND DISCUSSION

The result and discussion is based on 12 simulation carried out and grid sensitivity study for various distributor configurations. The whole simulation time took about 40.4 h. Data obtained from the simulation for the whole SFB that was imperative in this study were tangential velocity, radial velocity, axial velocity and also the pressure drop of the system.

Grid sensitivity study: Three different meshing schemes designated as A, B and C consisting different number of elements were generated in GAMBIT. These grids are studied for their independence based on variation in distributor pressure drop which was one of the major performance criterions in fluidization. The summary of the study is presented in Table 2 and Fig. 5.

It was found that all schemes are highly independent of meshing density as the difference between calculated distributor pressure drops were less than 0.01%. Therefore scheme C is chosen based on the faster computation time.

Resultant velocity distribution: Upon entering the tangential inlets of the plenum chamber, the air swirls and flows upwards in the axial direction before deflected by the distributor blades into the bed. The gaps between two consecutive blades result in velocity jet and swirling motion is created inside the bed due to the confined circular path (annular region). The resultant velocity profile of various configurations is shown Fig. 5a, taken from the interrogation area which is 45 mm above the distributor enclosed by the cone and column wall while Fig. 5b depicts an example of velocity vector (taken from 45-13.5° distributor configuration).

From Fig. 6a, it was found that all resultant velocity is low near the centre body (left) before rising steadily along the radius. It was found that conventional distributors (0° radial inclinations) have skewed velocity distribution with higher degree of skewness for larger number of blades. This skewed distribution is due to air massing at outer periphery of the bed as a result of centrifugal force generated by the swirling motion. On the other hand, distributors with radial inclination

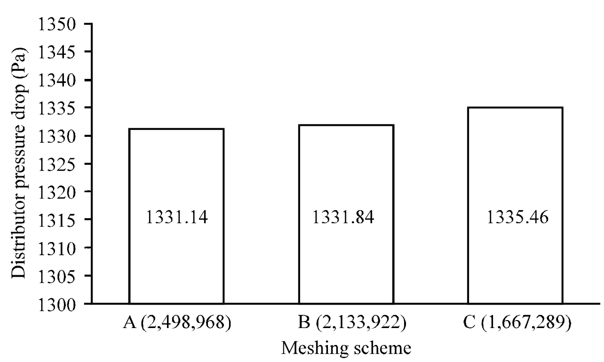

Fig. 5: Comparison between meshing schemes

Table 2: Summary of grid and iteration details

Scheme	Iteration	Total iteration	Simulation time (h)	No. of elements
A	25	345	2.36	2,498,968
B	26	310	2.25	2,133,922
C	23	315	1.45	1,667,289

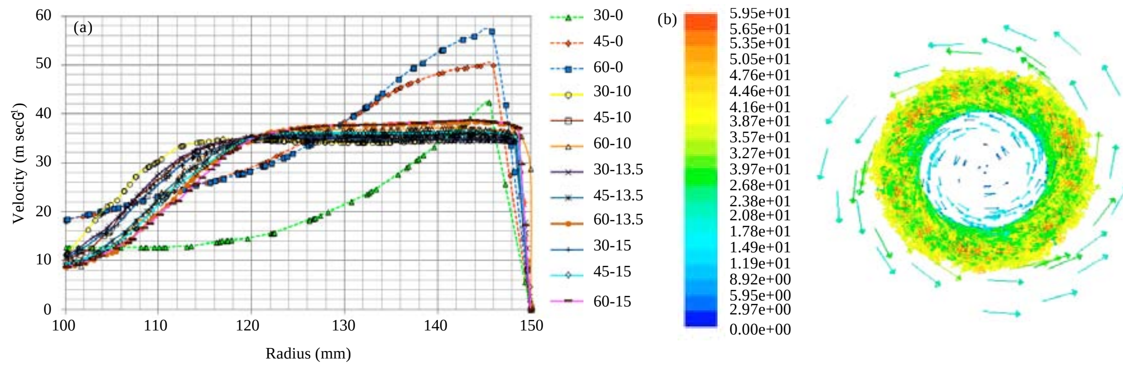

Fig. 6(a-b): (a) Velocity distribution for all distributor configurations and (b) Velocity vector extracted from 45-13.5° case (45 mm above distributor)

exhibits similar trend-steady increase in velocity magnitude from the centre body before reaching plateau beyond 115 mm radius. It is evident here that the radial inclination improves velocity distribution towards better uniformity in the annular region. It was also found that combination of lower number of blades with low radial inclination shows slightly higher uniformity. Higher number of blades has higher velocity magnitude due to the orifice effect but reduces uniformity. The velocity vectors in Fig. 6b shows that the swirling flow dominated a major portion of the chamber except near the centre of the column. Although radial and axial velocity exists, the magnitude is smaller and less pronounced, as discussed in the following section. Another important finding here is that the effect of number of blades is less prominent in comparison to the blades radial inclination. Therefore the following section will address the effect of radial inclination for a given number of blades.

Tangential velocity distribution: Tangential velocity represents the velocity of the swirling air flow in the annular region of the bed. Figure 7 shows the effect of radial inclination for fixed number of blades: (a) 30 blades, (b) 45 blades and (c) 60. It was found that the magnitude tends to increase along its radius, approaching the bed's wall. The higher magnitude of this component due to larger fraction of momentum on the horizontal direction compared to axial direction. The higher tangential velocity is imperative because momentum on this direction creates swirling motion inside the bed due to the circular path.

While the 0° distributor result-in severe skew to the wall (as a result of centrifugal force), the radial inclination promotes better uniformity with small differences between 10 to 15° radial inclination. As expected, larger number of blades (which has smaller open area of flow) possesses higher velocity magnitude due to orifice effect.

Radial velocity distribution: Radial velocity is another velocity component which is created as the air enters the bed through the distributor. It represents the velocity distributed along the blades from centre of the bed towards the column. In a SFB, tangential velocity creates swirling where centrifugal force generated will push the air outwards to the column wall. It was reported from experimental works (Sreenivasan and Raghavan, 2002) that this centrifugal force will push particles in an actual system to the bed wall. This results the particles to mass at the outer

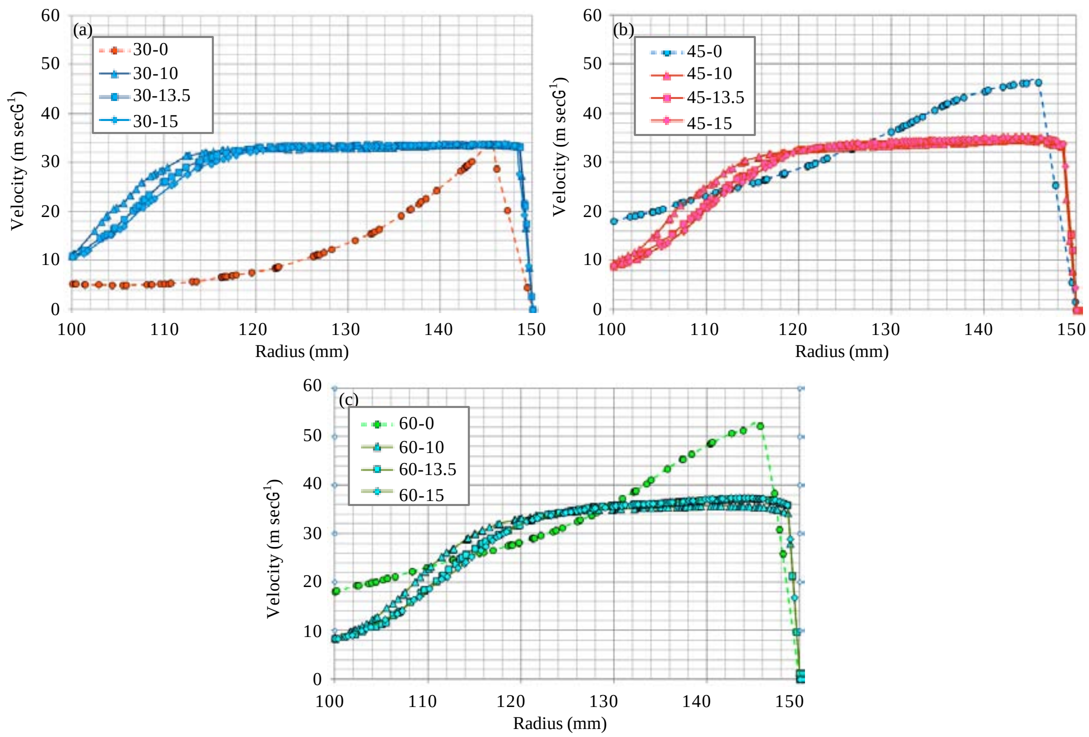

Fig. 7(a-c): Tangential velocity distribution for (a) 30, (b) 45 and (c) 60 blades

periphery of the bed leaves while the annular region near the centre body left exposed where significant amount of fluidizing air bypasses the bed. Hence, inward momentum to balance this centrifugal force is necessary.

Figure 8 shows radial velocity distribution for 30, 45 and 60 blades. However, the effect of radial inclination is small between 10 to 15° though higher radial inclination has slightly larger velocity magnitude. However, the magnitude of radial velocity (average) is only about 15% compared to that of tangential velocity.

Axial velocity distribution: Axial velocity represents the velocity in axial direction, as a result of blade opening in horizontal plane. In an actual SFB system, the axial velocity is responsible for fluidization of the particles. In the present study, the magnitude of axial velocity is about 25% of the tangential velocity due to the low injection angle of air through the distributor.

Referring to Fig. 9, some negative values of velocity were obtained at the location where the centre body attached to the inner part of the distributor blades. These negative values indicate air is flowing in the reverse direction at the distributor surface. This may be attributed to: (1) sudden expansion at the area adjacent to the cone, as the cone angle is about 56° and (2) negative flow due to low pressure as a result of centrifugal weight of air as discussed before. The velocity increased steeply to a maximum before gently declining, providing a fairly uniform distribution in half of the annular region.

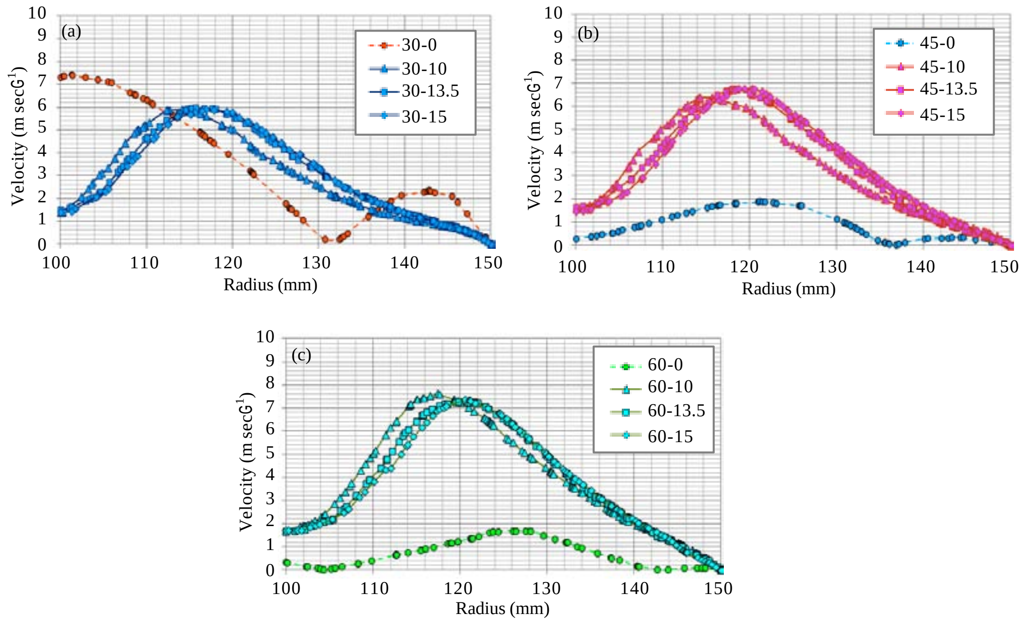

Fig. 8(a-c): Radial velocity distribution for (a) 30, (b) 45 and (c) 60 blades

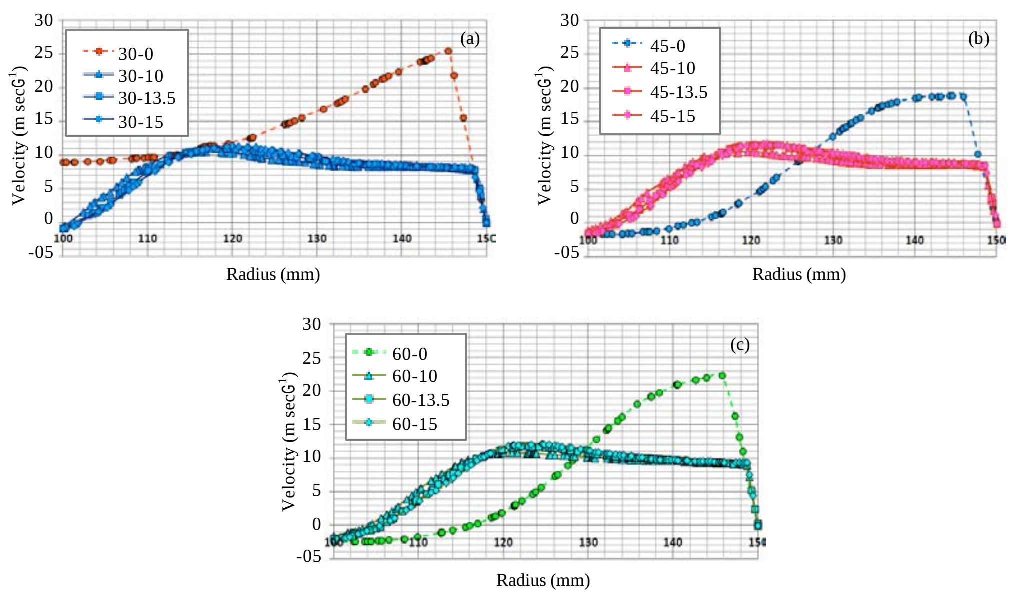

Fig. 9(a-c):Axial velocity distribution for (a) 30, (b) 45 and (c) 60 blades

Pressure drop: The data of pressure drop were calculated by taking the difference of average of static pressure between the upper and lower planes, i.e., before and after the distributor, is shown in Fig. 10.

Figure 10 depicts distributor pressure drop for all cases investigated. In the present study, distributor pressure drop accounts for the amount of energy spent to overcome the flow resistance due to the distributor geometry and configuration. It was found that distributor without radial

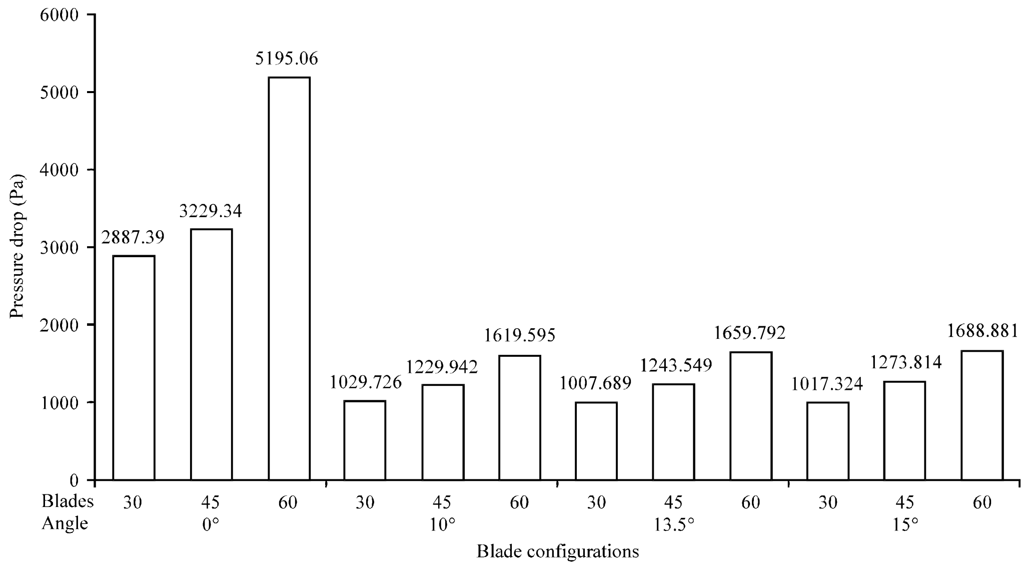

Fig. 10: Distributor pressure drop between configurations

inclination (0°) possesses the highest pressure drop compared to distributors with radial inclination. Interestingly, distributors with radial inclination have comparable pressure drop for a given number of blades. Generally, distributor with 60 blades has higher pressure drop compared to 45 and 30 blades naturally due to lower effective area for flow to take place. Smaller effective area imposes higher resistance, hence resulting higher pressure drops, though this is not true for 30 blades with 10° radial inclination which may be attributed to numerical error. The total reduction in pressure drop is significant, ranging from 40% (for 45 blades) up to 60% (30 and 60 blades) likely due to gradual flow expansion in radially inclined distributors.

CONCLUSION

The extracted results from nine (12) simulated cases varying on the various distributor configurations from 0° (no radial inclination) to 15° radial inclination. The complex, 3-D velocity profile in a SFB was resolved to tangential, radial and axial velocities and studied individually led to several important findings. Qualitatively, radial inclination promotes better flow uniformity and capable to augment the radial velocity component and provide inward momentum to reduce intense centrifugal force generated by the tangential velocity component. Distributor without radial inclination has skewed profile which may affect mixing and the degree of solid-fluid contact in an actual system. The magnitude of tangential velocity component accounts for about 60% due to low angle of air injection (12°). Radial inclination of distributor was also found to have lower pressure drops and the variation of pressure drop between all distributors with radial inclination is relatively low.

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