COMPUTATIONAL STUDIES ON EFFECT OF NOVEL ACCELERATING PERFORATED DISTRIBUTOR ON FLUID DYNAMIC CHARACTERISTICS OF CIRCULATING FLUIDIZED BED RISER

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ABSTRACT

The present work is associated with Circulating Fluidized Bed (CFB) technology, related to the energy sector. The applications of CFB technology span across wide range of areas such as boiler, gasifier, combustor, dryer, etc. In the present paper, CFD simulations using ANSYS-Fluent 15 were performed to study the effect of novel accelerating perforated distributor on fluid dynamics characteristics like pressure drop along the riser and distributor, suspension density variations along the riser of CFB. The simulation results were also used to compare qualitatively and quantitatively the dead-zone formations in the four corners of riser of square in cross section placed above the distributor plate for accelerating and normal distributor plates. The riser along with distributor was modeled using Pro-E 5.0, and it was meshed in ICEM CFD 15. Post processing simulations were performed using Fluent 15. 3D CFD simulations were performed on the CFB riser of cross section 0.15 m × 0.15 m and height 2.85 m. Eulerian model with Syamlal-O'Brien phase interaction scheme was used to simulate the two phase flow (air + sand mixture flow). RNG k-ε model was used for turbulence modeling of the flow inside the riser. Modeling and simulations were performed for normal (conventional) perforated distributor plate and results obtained were compared with available experimental data. In this way, after validation of computational results, further CFD simulations were performed for novel geometry of accelerating distributor plate. It is observed that suspension density (particles' concentration) decreases with increase in height of the riser in case of accelerating distributor plate. The objective of reduction in the dead-zone formation just above the distributor plate was achieved through novel accelerating distributor, which in-turn is expected to increase particles' participation in combustion which takes place in oxygen rich middle portion of CFB riser and subsequently increases heat transfer rate in the CFB riser. Results obtained for novel accelerating distributor plates were compared with normal (conventional) distributor plate and swirling distributor plate.

INTRODUCTION

The present work is associated with Circulating Fluidized Bed (CFB) technology, which is a technology related to the energy sector. It is a well known technology due to fuel flexibility, pollution control, large gain in thermal and combustion efficiency. The applications of CFB technology span across wide range of areas i.e. boiler, gasifier, combustor, dryer, etc. Its application as boiler in the power plants is among the most important applications. A large number of CFB units are installed for power generation throughout the world is reported by (P. M. Hupa, 2007). G. R. Grulovic et al (2008), A. K. Kolar and R. Sundaresan. (2002), R. Sundaresan and A.K. Kolar (2002), J. D. Pagliuso and G. Lombardi (2000), W. B. Fox et al (1999), D. Shi et al (1998), P. Basu, P. K. Nag (1996), P. Basu and P.K. Nag (1987), R. L. Wu et al (1987), have reported that heat transfer characteristics in CFB riser are the function of fluid dynamic characteristics. Hence, it is important to study the fluid dynamic characteristics of a CFB riser.

The variation in suspension density along the height of the CFB riser is a major fluid dynamic characteristic that affects the heat transfer rate in CFB riser, has observed as a proportional relationship between them (A. K. Kolar and R. Sundaresan, 2002, R. Sundaresan and A.K. Kolar, 2002, P. Basu and P. K. Nag, 1996). Higher suspension density at a particular height means more particles are suspended at that particular height and therefore, high heat transfer rate can be achieved there because of higher heat transfer coefficient of solid particles compared to gases. In a CFB riser, since most of combustion as well as heat transfer take place in Oxygen-rich middle and upper zones compared to Oxygen-deficient lower zone, it is advisable to have higher suspension densities in middle and upper regions of CFB riser. For a given operating conditions, the distribution of solid particles along the height of the riser and across the riser depend upon the density of particles, height of solid inventory, design of distributor plate including percentage opening area in the distributor plate (P. Kalita et al., 2013, B. Peng et al., 2011, Xi-Zhong et al., 2011, B. Peng et al., 2011, N. Hu et al., 2009, P. C. Josephkunju, 2008, D. Sathiyamoorthy and CH. Sridhar Rao, 2003, Z. Garncarek et al., 1997, F. Ouyang and O. Levenspiel, 1986, D. Geldart and J. Baeyens, 1985, D. Sathiyamoorthy and CH. Sridhar Rao, 1981, N. Upadhyay et al., 1981, S.C. Saxena et al., 1979, D. Sathiyamoorthy and CH. Sridhar Rao, 1977). The pressure drop across distributor plate is another important parameter that needs to be considered while designing the distributor plate since it affects the power consumption by blower and therefore, economics. Hence it is clear that the design of distributor plate significantly affects the fluid dynamic characteristics and therefore, heat transfer characteristics. The effects of variables like gas velocity, particle size, restitution coefficient, etc. have been considered by many researchers (Q. Wang et al., 2012, F. Taghipour et al., 2005, A. Samuelsberg and B. H. Hjertager, 1996), but the effect of distributor plate of square in cross section is limited to very few papers (B. Peng et al., 2011, Xi-Zhong Chen et al., 2011, K. P. Shete et al., 2014, B. Peng et al., 2011). It is observed from the literature that normal (conventional) perforated distributor plate, dead zones have been observed in four bottoms corners of CFB riser as well as just above the distributor plate, which in-turn suggests that some particles remain idle at those locations and neither participate in the combustion nor do they assist in the heat transfer taking place at middle and upper zones of CFB riser. In consideration of this, a design of novel accelerating perforated distributor plate has been proposed, with an objective to achieve improvement in fluid dynamic characteristics over conventional distributor plate by largely eliminating the dead-zone formations and having higher suspension densities in middle and upper regions of CFB riser.

RISER AND DISTRIBUTOR GEOMETRY

The primary objective of the present study is to design a distributor plate of 5 mm thick which is placed at the bottom of riser in order to produce the accelerated flow in the riser to minimize the dead-zone formation at four corners of riser walls and also just above the distributor plate. Riser with accelerating distributor plate of cross section 0.15 m × 0.15 m and height 2.85 m was designed and used for simulation purpose as shown in Fig.1. Sand is filled till the height of 0.196 m above the distributor plate. There is a provision of sand inlet of dimension 0.15 m × 0.15 m, which allows the sand from cyclone separator to re-enter the riser domain to facilitate circulating fluidization.

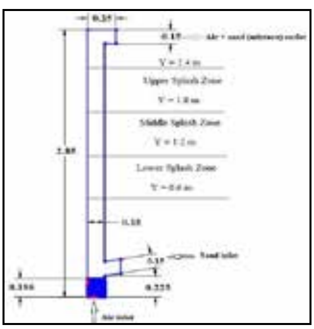

Fig. 1. Riser dimension and geometry

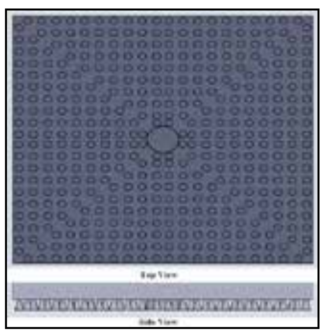

Fig. 2. Novel perforated accelerating distributor plate

As shown in Fig.1, air + sand (mixture) outlet of the riser is present at the top of the riser column whose dimension is 0.15 m × 0.15 m also act as the inlet to the cyclone separator. A shown in Fig.2, there are 8 zones with 55 orifices in each zone. This design was intended in reducing dead-zone formation above distributor plate. The central core (orifice) has a diameter of 0.016 m. The purpose of this core orifice is to lift the large amount of sand towards middle and upper zones. Opening area of the distributor plate was maintained same as 25.46% as mentioned in (K. P. Shete et al., 2014, R. S. Patil et al., 2011). To facilitate accelerating flow, the smaller orifices were frustum in shape. The diameter at bottom of the orifice is 4 mm and is tapered to a diameter of 2 mm at the top thus getting frustum shape and connected to the riser section as shown in side view of Fig.2. The height of the frustum is 5 mm, which is the thickness of the distributor plate.

MESH STRUCTURE AND GRID-INDEPENDENCE TEST

As shown in Fig.3(a), the central core of riser section is made up of hexahedral cells; these cells are supported by pyramid cells which connect to tetrahedral cells placed near to the riser wall. To incorporate the velocity gradients in the accelerating nozzles and their exits, adequate care was taken to regulate the initial size and growth of tetrahedral cells from the exit surface of orifices till the inner hexahedral core. The riser with novel distributor plate contained 500925 nodes with maximum cell size of 0.006 m in the central region whereas the riser with conventional distributor plate contained 378427 nodes (K. P. Shete et al., 2014). The accelerating nature of distributor geometry required much more number of nodes compared to the riser with conventional distributor plate and the swirling distributor plate (404082 nodes, K. P. Shete et al., 2014). Fig.3(b) shows the cut-plane of mesh and it shows that the growth ratio is controlled in the present mesh. Also, there is a use of density function with mesh size of 2 and growth ratio of 1.2, located at the distributor plate region from height y = -5 mm to y = 10 mm. Tetra size ratio and height ratio are employed as sizing functions to regulate the growth of surface trias and position of next element along with its size normal to the surface from where the meshing starts, respectively. These helped in capturing the boundary functions as it was observed that all nodes are present in log law region and coupling the mesh with scalable wall functions yielded in physically correct results. Hence the present mesh and also based on previous validation (K. P. Shete et al., 2014) will be acceptable for the current simulation due to the use of density function for the accelerating region.

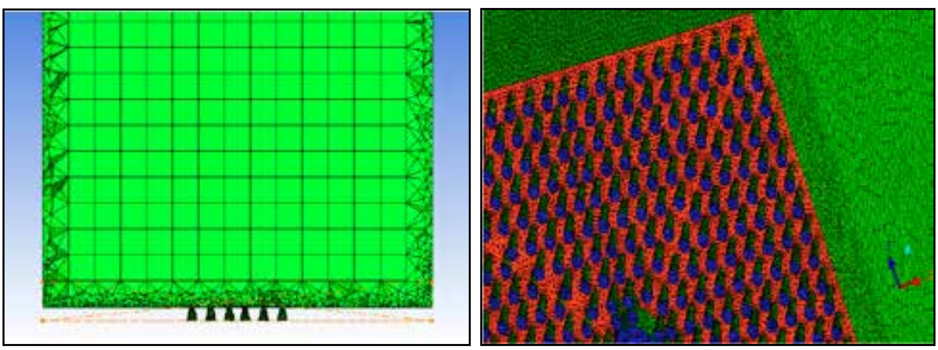

Fig. 3(a). Cut-plane of 8-zone distributor plate   Fig. 3(b). Mesh near the 8-zone distributor plate region

COMPUTATIONAL FLUID DYNAMICS SIMULATION SET UP

There are several models for multiphase flows in which the flow can be described. Eulerian-Eulerian multiphase flow model (B. Peng et al., 2011, A. Almuttahar and F. Taghipour, 2008) was selected for the simulation and the differential equations of continuity and momentum were solved for the mixture since different phases are treated mathematically as interpenetrating continua. Conservation equations for each phase are derived to obtain a set of equations, which have similar structure for all phases. These equations are closed by providing constitutive relations that are obtained from empirical information, or, in the case of granular flows, by application of kinetic theory. The appropriate viscous model is selected for both phase combined. The drag force on sand due to air was specified by a correlation. Drag correlation calculates drag coefficient based on slip velocity. This value is then used to calculate forces on the secondary phase (ANSYS Fluent 15). To model the drag force between fluid and solid phases, three models are popular, Wen-yu, Gidaspow and Syamlal-O'Brien (ANSYS Fluent 15). The Wen-yu model is applicable only for dilute phase models, whereas the Gidaspow model is suitable for dense fluidized beds (S. Benzarti et al., 2012). In the CFB riser, the bottom zone is expected to be dense whereas middle and top zones are expected to be diluting in terms of solids concentration. That is, the multiphase flow is neither only dilute nor only dense, but a mixture of both over the height of the riser and to account for such fluidization behavior, Syamlal-O'Brien drag correlation was used in the simulation (M. Muthu Kumar and E. Natarajan, 2008). Syamlal-O'Brien viscosity model is applied for the granular phase with a packing fraction of 0.62 and the momentum transfer model between the two phases (inter phase interaction) is Syamlal-O'Brien model with a collision coefficient of 0.9 (X. Zhou et al., 2013). The two-equation RNG k-ε model is selected for turbulence modeling for the riser. Turbulence modeling is an essential part in numerically solving the governing flow equations as it is used to find closure to the additional terms generated in the RANS equations which behave like stress terms. Since the multiphase flow is highly turbulent, the RNG model was selected specifically to include the effects of swirl/acceleration in the riser near the walls. The function of RNG k-ε model is augmented for near-wall region by applying Scalable wall functions. In the present study, scalable wall functions are used as the grid present in near-wall region is not strictly in the logarithmic layer and scalable wall functions augment the advantages of standard wall functions. Y+ value for continuous phase was maintained below 300 for all simulations. To deal with low Y+ values, scalable wall function was used.

In this simulation, the primary phase is taken as air and the secondary phase is considered as sand. Sand is taken as granular in nature with a diameter of 46 µm which was the mean diameter of particles in experimental data (R. S. Patil et al., 2011) and density of 2600 kg/m^3 which puts it under Geldart B particle as mentioned in the literature review. Boundary conditions used were as follows-inlet mass flow rate of 0.11 kg/s for air and gauge pressure 0 Pa, gas outlet as pressure-outlet with gauge pressure 0 Pa, mass inlet with a mass flow rate of 0.44 kg/s with a volume fraction of 0.62 and turbulent intensity as 5%, initial bed with volume fraction as 0.62, static bed height of 0.196 m above the distributor plate. Phase coupled SIMPLE pressure-velocity coupling was used. Discretization scheme used was first order upwind. As reported in (K. P. Shete et al., 2014) for CFB riser with conventional distributor plate, the CFD model with 378427 nodes and with the 1st order discretization scheme provided qualitatively and quantitatively similar results to those of experiments. Therefore, to avoid excessive computational time with the 2nd order discretization scheme, in the present work the 1st order discretization scheme was chosen.

The authors have validated the simulation setup in (K. P. Shete et al., 2014). The experimental data was available for normal (conventional) perforated distributor plate. Two grids, with 254267 nodes and 378427 nodes were generated in (K. P. Shete et al., 2014). The results from simulations of grid with 378427 nodes, match qualitatively and quantitatively with the available experimental data (Fig.1, K. P. Shete et al., 2014). For average size of particles was 46 µm, a grid size of around 0.005 m could be considered the finest mesh (T. Li et al., 2014). Hence, 0.006 m (~13 times particle diameter) was chosen as maximum grid size in the central hexacore region of CFB riser with conventional distributor plate (K. P. Shete et al., 2014) considering the fact that 378427 node mesh had mesh size close to rule of thumb for gas solid flows (T. Li et al., 2014) and the observations reported in (T. Li et al., 2014), it was felt that refined mesh with 378427 nodes and 0.006 m cell size was sufficient to provide accurate results. Hence, further simulations with even more refined mesh with 0.005 m cell size were not performed (K. P. Shete et al., 2014). The same grid type was selected for riser with novel swirling (K. P. Shete et al., 2014) and for accelerating distributor plate in the present study, with maximum cell size of 0.006 m in the core to accurately predict the results.

RESULTS AND DISCUSSION

It is known that the riser column is divided into three splash zones; lower, middle, and upper (R. S. Patil et al., 2011) as shown in Fig.1. Two pressure taps of water manometer were fixed over each splash zone of height 0.6 m. The basic criteria to judge the performance of a circulating fluidized bed boiler's riser section is to evaluate the average cross-sectional suspension density at the three splash zones along the riser column. It can be said that if more the amount of particles between two pressure taps of the water manometer, there is an increase in pressure drop values in that splash zone which in turn result in higher suspension density in that zone. During actual combustion of particles greater suspension density in oxygen rich middle and upper region implies more amount of heat will be generated in those zones and subsequently will increase amount of heat exchange between the riser products and the fluid medium present inside the riser tubes.

Fig.4 shows the contour plot of volume fraction of phase 2 (sand) along the height of the riser. Fig.5 shows the contour plot of volume fraction of sand on the accelerating distributor plate. The small patch of sand on the bottom left corner of the distributor plate could be an indication of dead zone formation in the lower denser zone.

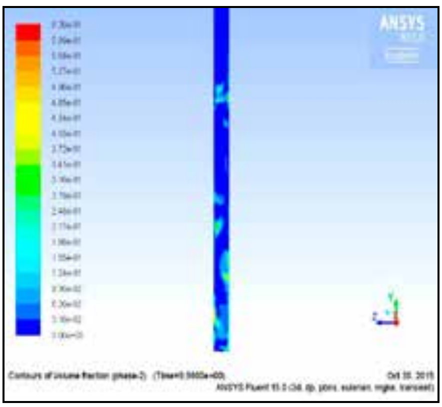

Fig. 4. Contour plot of volume fraction of sand

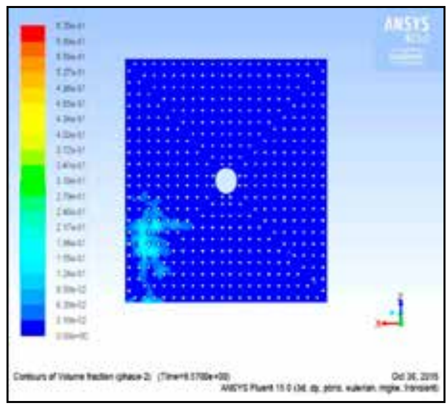

Fig. 5. Contour plot for volume fraction of sand

However as shown in Fig.6 the flow is periodic in nature, hence contours plot shown in Figs.4 and 5 were varying with time. As shown in Fig.6 it has been observed that variation in the mass flow rate at outlet of riser during the interval 20s to 56s was almost steady when values were reported at every 0.25s. Hence it has been predicted from Fig.6 that the initial mass of 8 kg has fluctuated up to 20 seconds (20s) and then the average mass inside the riser from 20s to 56s would be 6.80 kg. Since as shown in Fig.6, the flow was periodic in nature, time averaged property like pressure drop along each splash zone during the interval 20s to 56s was calculated to predict suspension density at the three specified zones. The values of suspension density in each zone are calculated by taking the mean values of pressure drop along the height of each zone obtained along a line 0.001 m from riser wall. Time averaged pressure drop in each zone of 0.6 m height was used further to obtain average suspension density for that zone and represented as suspension density at y = 0.9 m for lower splash zone, y = 1.5 m for middle splash zone, and y = 2.1 m for upper splash zone as shown in Fig.7.

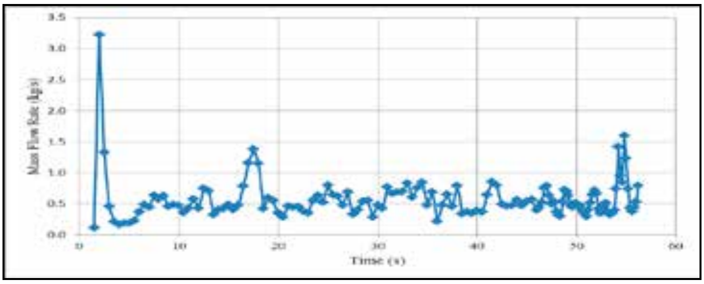

Fig. 6. Mass flow rate at outlet

By using novel accelerated distributor plate design, a new trend in the suspension density variation along the height of riser is observed as shown in Fig.7. It indicates that the accelerating distributor geometry (8-zone accelerating) produces a similar trend in the suspension density plot if compared with conventional distributor plate (experimental data in Fig.7). However due to flow being accelerating in nature, the suspension density at middle and upper splash zones was higher and observed to be lower in the lower splash zone than conventional distributor geometry. Comparing the results with the 4-zone swirling geometry proposed in (K. P. Shete et al, 2014), it can be seen that the trend in the 4-zone swirling distributor leads to lower suspension densities in the middle oxygen rich zone which is favorable for better heat transfer characteristics in this region and hence better performance if novel accelerating distributor is used. But in the lower regions, suspension density is observed more with accelerating distributor than 4-zone swirling distributor while both the distributors show almost same amount of suspension density at upper splash zone. Hence there will be disadvantage of dead zones formation in the lower regions with novel accelerating distributor if compared with 4-zone swirling distributor. Taking into consideration the advantages of swirling and novel accelerating distributor plates design; it also hints that combination of swirling and novel accelerating distributor plate designs could be very promising in order to eliminate the dead zones and to increase the sand particles suspended in the oxygen rich middle splash zone.

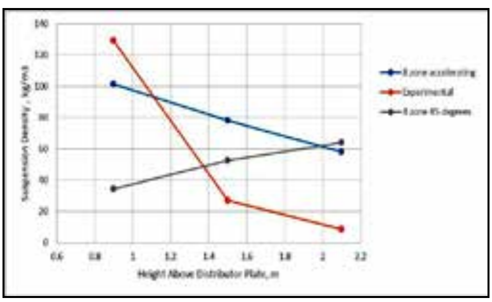

Fig. 7. Suspension density for different distributor plates

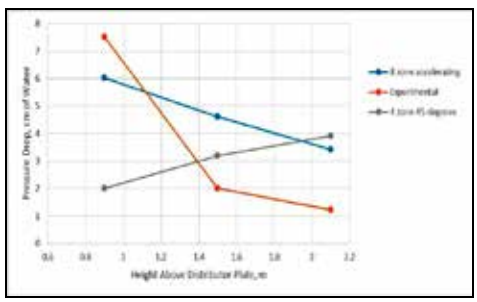

Fig. 8. Pressure drop above the distributor plates

Fig.8 gives the information about the pressure drop along the height of each splash region in cm of water level required to maintain the flow in the riser. The conventional distributor plate and 8-zone novel accelerating distributor plate designs have a similar trend in pressure drop plot. Pressure drop across the normal (conventional) distributor plate, 4-zone swirling distributor plate, and novel 8-zone accelerating distributor plate was found to be 0.10 cm, 3.85 cm, and 2.62 cm respectively. Hence 8-zone novel accelerating distributor and 4-zone swirling distributor plates require more power input to the blower to maintain the flow inside riser column.

CONCLUSION

In the present work, the design of novel 8-zone accelerating distributor plate geometry was analyzed. The simulation was conducted till 56s. The mass outlet and inlet calculations show agreement and thus provides confidence that the riser is free from initial transient effects and has attained pseudo-steady state after 20s of simulation. By studying the time-averaged suspension density plots, it is concluded that the 8-zone novel accelerating distributor plate was efficient in holding more sand particles in the oxygen rich middle splash region than other two distributor plates. Suspension density in the lower splash zone with novel distributor plate found to be lesser than normal (conventional) distributor; hence it indicates that there are less chances of forming the dead zones with novel distributor plate if compared with dead zone formation with conventional distributor. Chances of formation of dead zones with swirling distributor will be very less among the three distributors since suspension density in the lower splash region oberved to be very less with swirling distributor. Hence it is concluded that combination of swirling and novel accelerating distributor plate designs could be very promising in order to eliminate the dead zones and to increase the sand particles suspended in the oxygen rich middle splash zone. Pressure drop across the novel 8-zone accelerating distributor plate and 4-zone swirling distributor plates found to be 26 times and 38 times greater than pressure drop observed in case of normal (conventional) distributor. This indicates that power required by blower to fluidize the steady bed will be more in case of 4-zone swirling and 8-zone novel accelerating distributors.

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