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THE EFFECTS OF DISTRIBUTOR DESIGN ON THE SOLIDS DISTRIBUTION IN A CFB RISER

Jesse Zhu* Jing Xu†
Botao Peng‡ Chao Zhang**

*University of Western Ontario, zhu@uwo.ca
†The University of Western Ontario
‡The University of Western Ontario
**The University of Western Ontario

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Jing Xu, Botao Peng, Chao Zhang, Jesse Zhu*

Particle Technology Research Center,
The University of Western Ontario, London, ON N6A 5B9

ABSTRACT

The influence of gas distributor design on the gas-solids flow structure was investigated in a rectangular CFB riser. The gas distributor was altered five different ways. The results show that the distributor design had significant effects on the solids distribution. The changed flow structure was maintained from the entrance to the riser top. Altering the gas distributor was an effective and practical method to change the flow structure. This study may be beneficial to CFB design and operation.

INTRODUCTION

Because of the advantages of good particle mixing, heat transfer characteristics and continuous powder handling ability, circulating fluidized bed has found its way in wide application in the chemical, petrochemical, metallurgical, environmental and energy industries (1). Solids distribution in CFBs has attracted great interests not only from engineers in industry, but also from scholars in academic areas. To understand the flow structures in the CFB risers, a significant number of scientific studies focusing on the axial and radial solids distributions, in terms of the solids concentration and particle velocity, have been conducted in risers (2-6). The term of "core-annulus" flow structure was commonly employed to describe flow patterns in CFB columns as lower concentration in the center while much denser in the wall region at all axial locations (7). It has been found that more uniform axial and radial solids flow structure in the riser might lead to shorter and more uniform solids (and gas) residence time, which potentially results in a better reactor performance. Consequently, the non-uniform "core-annulus" structure might amount to an extensive solids backmixing which lowers the gas-solids contact efficiency as well as the chemical reaction efficiency (7). Moreover, the influence of this flowing pattern on heat transfer is also significant. Thus, good understanding of the flow structure and studying the detailed mechanisms of the flow structure are of great importance to the design and operation of CFB.

The flow structure in the entrance region is critical to the overall particle distribution in the whole CFB riser. However, very few studies have been conducted on the influences of gas inlet design on the flow structure in CFBs. In this study, specially designed experiments in the CFB systems will be conducted in a 2-dimentional CFB system with special gas inlet arrangements. The 2-D CFB is proved more uniform of the lateral solids distribution than that of the cylindrical risers (8), and is considered as a useful means of visualizing the flow structure in the riser column (9-11). The effect of the gas distributor design on the flow fields might be more evident when compared with the original solids distribution in the 2-D CFB riser. The solids concentration and particle velocity were measured by the use of a pair of optical fiber probes. Photos of the riser column were taken to visualize the flow structure and the CFD simulation was also conducted to help illustrate the mechanisms of the flow structure in the CFB riser.

EXPERIMENTAL APPARATUS

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A rectangular CFB system was designed and setup, as shown in Figure 1, to conduct the experiments. The riser is a rectangular column with a 19×114 mm cross-section and a 7.6 m height. FCC particles with a Sauter mean diameter of 67 μm and a particle density of 1884 kg/m^3 were used. The primary air at ambient temperature and pressure was supplied to the windbox located in the riser bottom with a small stream of steam merged in to control the humidity of the gas fed into the riser to be between 70 to 80%, to avoid misleading effects due to electrostatic forces (12). The gas fed into the riser was monitored by a rotameter and a thermo-hygrometer. The solids circulation rate was measured by a device which is located at the top of the downcomer. By appropriately flipping over the two valves of the device from one side to the other, solids circulated through the system can be accumulated on one side for a given time period and then the solids circulation rate can be obtained.

Various steel slices designed with different rectangular holes are inserted between the riser and the perforated plate to implement the different gas inlet distributors. As Figure 2 shows, five different gas distributors were employed. With this special design, one can investigate the effect of inlet gas flow on the lateral solids distribution. In other words, one may study how the gas flow in the entrance affects the mechanisms of the formation of the core-annulus structure.

The local solids concentrations were measured with a multi-fibre optical probe, PV6, which was developed by Institute of Process Engineering, Chinese Academy of Sciences. With precise calibration and cross-correlation applied, solids concentration and particle velocity can be obtained. Details of the calibration process and velocity calculation were referred in literatures (13,14).

The solids concentrations were measured at 9 lateral positions located at y/Y = -0.98, -0.75, -0.50, -0.25, 0, 0.25, 0.50, 0.75, 0.98, in which y/Y is the dimensionless distance from the riser axis, and at 7 axial levels. To ensure the validity and repeatability of sampled signals, the sampling time at each position is 13.1 s with a frequency of 100 kHz and the measurements were repeated at least three times. In this study, the superficial gas velocity and solids circulation rate were controlled in the range of 3.5 to 8 m/s and 50 to 200 $kg/m^2 \cdot s$ respectively.

NUMERICAL METHOD

The 2-D Eulerian-Eulerian CFD model is used for the simulation of the CFB riser in this study. The mesh for the simulation is generated using Gambit 2.4. Quad grid system is used with finer mesh near the wall. The mesh in the inlet region is also refined since the change in flow parameters is great at the inlet region. The double-precision segregated, implicit formulation, unsteady solver is selected in this study. The governing equations are solved using finite volume approach. Phase coupled SIMPLE algorithm (15) is employed in pressure-velocity coupling. The power law scheme (16) is selected as the discretization method for all unknowns except volume fraction while QUICK (16) is used instead. The commercial CFD software Fluent 6.3 is used to carry out the simulations.

RESULTS AND DISCUSSION

Observation of the Flow Structure

The main gas entered into the windbox at the bottom of the riser and went through the perforated plate, called gas distributor, then into the riser column. The perforated distributor was altered by covering with a stainless steel sheet, which was designed to shelter partial of the gas distirbutor. Front view pictures of the solids distribution were taken from the face wall along the riser height, as shown in Figure 3. Originally, the gas was distributed with the distributor fully opened. The Figure 3(a) shows the flow structure in the upper section of the riser. It can be seen that the so-called core-annulus structure remain evident at the riser top. Solids were seen to be dilute and moving faster in the centre while much denser and slower close to the side walls. Almost all particles moved upward while some flowed downward at the side walls under high flux conditions. It was observed that there was no evidence of solids buildup or fall down on both face walls.

Two extreme conditions were studied with half-covered perforated plate. Figure 3 (b) and (c) display the profiles of solids distribution with left and right side opened distributors respectively. These two cases were designed to show obviously how the gas distributor effects the solids distribution and to reveal the mechanism of the flow structure. The photos clearly exhibit the flow structure in the riser. When the gas enters the riser from the left side, the solids distribution presents a left-dilute right-dense pattern at the entrance of the riser. This observation remains up to the riser top: the right side is full of particles while the left is nearly empty. When the left side is covered, the opposite flow pattern results. Once again the pattern is present along the whole riser: from the entrance to the exit. It was found that the symmetrical core-annulus structure was altered significantly from the gas inlet and the new flow pattern dominated in the whole column. The photos illustrate that the gas inlet has great influence on the entire flow structure, leading to distinctly different solids distributions at different inlet opening design. It also can be seen that the flow pattern produced at the gas entrance can be conveyed to the fully developed region and further to the riser exit.

Though the other types of altered distributions changed the conventional flow structure not as obviously as the afore-mentioned two extreme cases did, the variation was still evident. The solids distribution will be compared quantitatively in the following paragraphs.

Profiles of the Solids Distribution

The lateral solids concentration ran with the fully opened distributor were compared with the other four altered distributors respectively. The solids distribution in the lower section and the upper region are taken into account since the lower section is considered as accelerating region and expected to represent the flow behaviour nearby the riser entrance, while the upper section is believed to be fully developed region. The results of solids concentration profiles quantitively verify the observation described by the photos.

Figure 4(a) and (b) show the left opened and right opened distributor effect on the flow structure under U_g = 8.0 m/s and G_s = 100 kg/m^2·s. y/Y = -0.98 to 0.98 is defined as left to right as front view. As described in the observation section, the half opened-half covered distributors considered as the extreme conditions alter the solids distribution significantly. The solids concentration is symmetrical and quite uniform both at lower section and the upper region when fully opened distributor was used. However, the half opened distributors present solids distribution profiles as non-symmetrical and half high-half low. In Figure 4(a), , the solids concentration on the left side with left opened distributor is lower than that with fully opened inlet, while on the right side, it is opposite. It can be found that the left opened distributor distributes the solids differently from the fully opened distributor, moving the great number of solids particles from the left side to the right, and resulting in the left side solids distribution is dilute while the right side is much denser. In the fully developed region at the height of 5.33m, the solids concentration still displays the left-low right-high pattern, whereas, the left side local solids concentrations are higher than the concentrations with fully opened distributor. It can be easily found that the denser solids concentration at right side may cause solids particles to be accumulated on the right side wall and thereafter slower the upward particle velocity, which might result in lower net solids flux in the whole CFB riser. This explains why the local solids concentration along the cross-section for the distributor half opened is higher than that with fully opened distributor under the same solids circulation rate.

Similar observation is presented in Figure 4(b). It is obvious that the non-symmetric structure for the solids concentration profile for the distributor right opened is so significant that the solids concentration at left side is several times higher than that with fully opened distributor while almost the same on the right side. This flow structure is maintained up to the fully developed region. The difference for the concentrations with two types of distributor is still quite clear. One may notice that, the deviation is quite striking at the height of 0.76m where is close to the riser entrance. This might due to the structure of the solids inlet. Due to the wall effect, the solids concentration increase slightly close to the right side wall.

Figure 5 displays the comparison of the right opened and fully opened distributors under different operating conditions. The solids distribution along the whole riser is denser than the solids concentration under U_g = 8.0m/s shown in Figure 4(b), whereas, the right-dilute left-dense flow structure remains the same. However, since the superficial gas velocity is lower (5 m/s), the non-symmetric solids distribution caused by the non-symmetric gas distribution is not as obvious as that under higher gas velocity condition.In a word, the half opened distributor altered the solids distribution significantly and resulted in less uniform flow structure.

Figure 6 exhibits the comparison of solids concentration under the operating condition of G_s = 100kg/m^2·s and U_g = 8.0m/s when the sides opened and center opened distributors were employed. The solids distribution in the lower section is denser than that in the upper region. Figure 6(a) indicates the solids distribution with sides opened distributor. The sides opened distributor leads to lower solids concentration on the side walls and higher concentration in the center. It can be seen that, the solids concentration with the sides opened distributor is slightly lower than the concentration with fully opened distributor at the side walls and a little higher in the center. The gas enters into the riser from the two side openings and travel along the side walls playing the role as a “cushion” to reduce the wall friction acting on the solids particles and “pushing” the particles towards the center. The particles are carried by the gas and move upward as fast as the gas does in the wall region whereas introduces more contacting, compacting and turbulent in the center region. This has resulted in the dilute solids concentration at side walls but denser in the riser center. This type of distributor may be utilized to reduce the thickness of the “annulus” of the flow, lessen the number of particles buildup on the riser wall and uniform the lateral or radial solids distribution. The comparative experiment was conducted in the 2-D CFB and might also be extended to the conventional cylindrical CFB risers.

Figure 6(b) shows the solids concentration with center opened distributor used. In the entrance region, the profile of solids concentrations of center opened distributor is steeper than that of the concentration with the fully opened one. In another word, the center opened distributor altered the solids distribution to be lower in the center and higher close to the wall. Both of the two profiles show very high concentration at y/Y = -0.98, which might be due to the non-symmetrical structure of the solids inlet caused entrance effect. In the upper region, the profiles of solids concentration are almost symmetrical and much flatter than that at the riser bottom, nevertheless, present a parabolic shape. It is found that the solids concentration for center opened distributor is less uniform than that of the fully opened gas inlet, in common with the phenomena in the lower section of the riser. It also can be observed that the non-uniform flow structure is more obvious when the center opened distributor was used. It may be described as that the center opened gas inlet structure changes the solids distribution from the entrance and conveys this effect up to the top. It also may tell that gas distributor has significant effect on the flow structure and the center opened distributor aggravates the non-uniformity of the flow structure in the CFB riser.

Profiles of Particle Velocity

It is commonly believed that the gas velocity accounts for the particle velocity, therefore the profile of solids concentration. The particle velocity may reveal the mechanisms of the solids concentration distribution and hydrodynamics of the gas flow.

Figure 7 and 8 depict the lateral profiles of particle velocity. Under the superficial gas velocity of 8.0 m/s, the lateral profile of particle velocity with fully opened distributor is normally uniform at the upper section while parabolic at the entrance of the riser. The particle velocity profile is corresponding with the distribution of solids concentration, as a flat concentration profile is accompanied with a uniform velocity profile. Figure 7 presents the particle velocity profile with the center opened distributor under the operating condition of G_s = 100kg/m^2·s and U_g = 8.0m/s. It may be found that, the center opening inlet causes the solids particles to move faster in the center opened region and slower in the wall at the height of 1.27m and 4.32m when compared with the flat profile of the particle velocity with fully opened distributor. The difference between the profiles of the two distributors remains the same at the lower and upper region. It is of good agreement when compared with the profiles of solids concentration mentioned above, which is dilute in the center while denser close to the wall. Figure 8(a) show the particle velocities with the left opened distributor. At the riser bottom, the solids can be seen moving towards the right side wall dramatically then travelling upward clinging to the wall. The solids holdup on the right side is observed much denser than the left along the whole riser, while the profile of the particle velocity presents the feature of left-high right-low. Along the lateral direction from the right side to the left, the particle velocity decreases then rises steeply towards the left side wall. In the upper region, the half-fast half-slow flow pattern remains the same, as the local average particle velocity increases gradually from the right side wall and ascends sharply when “pass over” the center of the riser, then drops slightly on the left wall. When compared with the velocity profile with the fully opened distributor, the asymmetric structure is obviously divided into two halves. It is evident that the left side particle velocity is much higher than that at the right side, especially at the very bottom of the riser. Contrary to Figure 8(a), Figure 8(b) displays the effect of right opened gas inlet, showing that the particle velocity profile is clearly higher in the right side than in the left side, which is accordant with the opening structure of the distributor.

The gas enters into the riser from the opening of the distributor and dilutes the solids concentration where it travels through since the gas accelerates the solids particles and may result in less compact for the solids. The mixture of gas and solids moves faster in the dilute region as the flow resistance is supposed to be low in the dilute region. Thereafter, the gas tends to keep its way along the dilute region. The movements of gas influence the motion of solids particles, affecting the particle velocity and so as the solids concentration.

Comparison of Experimental and Numerical Results

The solids concentration and particle velocity were also studied numerically. A set of governing equations were solved to obtain the velocities and concentrations for the gas-solids two phases. The standard k-□ turbulence model with wall functions approach was applied for both phases in the simulation. Figure 9 presents the experimental and numerical results of the solids distribution for the fully and center opened distributors. Figure 9 (a) compares the experimental solids concentration and the simulated profile at the fully developed region, located at the height of 5.33m. Both profiles are flat excepting slightly variation on the side walls. Figure 9 (b) show the alteration of the center opened distributor. The numerical results show that the solids concentration is not even but curved as lower in the center and higher in the wall, which is also verified by the experimental results. The effects of the gas inlet distributor is shown significantly both by the experiments and simulation in the fully developed region, which means the distributor maintains the alteration of the solids distribution all along the CFB riser up to the top. The same can be convinced by the particle velocity profiles also plotted in Figure 9 (a) and (b). The profile of particle velocity is close to the reversed solids concentration profile. For the fully opened distributor, the local average particle velocity is almost uniform along the lateral direction while decrease slightly when close to the wall. The experimental result is fairly in agreement with the simulated profile. Less uniform profile of particle velocity is observed in Figure 9 (b) due to the effect of the center opened gas distributor. The particles are moving much faster in the center than at the sides and present a symmetric profile which is corresponding with the numerical simulation results.

CONCLUSION

The effects of the distributor design on the solids distribution was studied in the 2-D CFB riser. Five types of gas inlet arrangements were employed: (1) fully opened; (2) left opened;

(3) right opened; (4) sides opened; (5) center opened. The solids distribution, in terms of solids concentration and particle velocity, was measured by optical fiber probes and investigated experimentally and numerically. The fully opened distributor was considered as the original condition, the other four types of special designed distributors were compared with the unaltered one.

With the comparison of the profiles of solids concentrations and particle velocities for different distributors, some beneficial results may be concluded from this study. The structure of the gas inlet distributor has an important effect on the solids distribution along the whole CFB riser, especially in the riser bottom region. The profiles of the lateral solids distributions with different gas distributors are distinct: the solids concentration and particle velocity along the lateral direction were quite uniform for fully opened distributor, while the left side opened or the right side opened gas inlet structure caused the profiles of solids concentration to be half-dilute half-dense, and the particle velocity to be half-high half-low; the center opened distributors leads to symmetric center-dilute wall-dense distribution of solids concentration and center-fast wall-slow pattern of particle velocity, whereas, reversed profiles of concentration and velocity were produced by the sides opened distributor. The new distribution formed in the riser entrance was conveyed and maintained up to the fully developed region, thereafter, the top of the riser. Moreover, the alteration of the solids distribution can be produced under different superficial gas velocities and solids circulation rates. The results also show that the profile of the gas is the main reason dominating the solids distribution in the CFB riser, accounting for the profiles of solids concentration and particle velocity. The distribution of the gas dictates the flow structure in the riser column and might have more significant effects over the “inherent” wall effect. The gas conveys the particles, dilutes the solids concentration where the gas travels by, and remains the effects up to riser. The conclusions obtained in the 2-D CFB riser are also applicable in cylindrical CFBs, and beneficial to improve the design and operation of CFB reactors.

REFERENCES

1. Grace, J. R. and Bi, H. T., 1997. Circulating Fluidized Beds. London, Chapman and Hall.
2. Bai, D. R., Jin, Y., Yu, Z. Q. and Zhu, J. X., 1992. Powder Technology 71, 51-58.
3. Bai, D. R. S., E.; Masuda, Y.; Nakagawa, N.; Kato, K., 1996. Chem Engr Sci 51(6), 957-966.
4. Yerushalmi, J., Turner, D. H. and Squires, A. M., 1976. I&EC, Proc. Des. Dev. 15, 47.
5. Li, Y. and Kwauk, M., 1980. The Dynamics of Fast Fluidization. In: Grace, J. R. and Mstsen, J. M., Fluidization, Plenum Press, New York, pp. 537.
6. Hartge, E.-U., Rensner, D. and Werther, J., 1988. In: Basu, P. and Large, J. F., Circulating Fluidized Bed Technology II, Pergamon Press, Toronto, pp. 165-180.
7. Bai, D., Shibuya, E., Masuda, Y., Nishio, K., Nakagawa, N. and Kato, K., 1995. Powder Tech 84, 75-81.
8. Xu, J. and Zhu, J., 2009. Experimental Study on the Distribution of Solids Concentration in a Rectangular CFB. Chemical Engineering Science (submitted).
9. Arena, U., Cammarota, A. and Marzocchella, A., 1989. J Chem Engr Japan 22, 236-241.
10. Park, A.-H., Bi, H. and Grace, J. R., 2002. Chemical Engineering Science 57, 153-162.
11. Pallares, D. and Johnsson, F., 2006. Chemical Engineering Science 61, 2710-2720.
12. Mehrani, P., Bi, H. T. and Grace, J. R., 2005. Journal of Electrostatics 63, 165-173.
13. Liu, J., Grace, J. R. and Bi, X., 2003. AIChE Journal 49, 1405-1420.
14. Zhang, H., Johnston, P. M., Zhu, J.-X., De Lasa, H. I. and Bergougnou, M. A., 1998. Powder Tech 100, 260-272.
15. Vasquez, S. A. and Ivanov, V. A., 2000. Fluids Engineering Division Summer Meeting. Boston, Massachusetts.
16. Patankar, S. V., 1981. Numerical Heat Transfer 4, 405-425.

LIST OF FIGURES

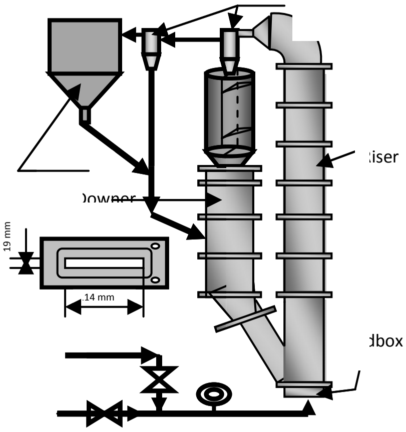


Figure 1. Schematic of 2-D CFB

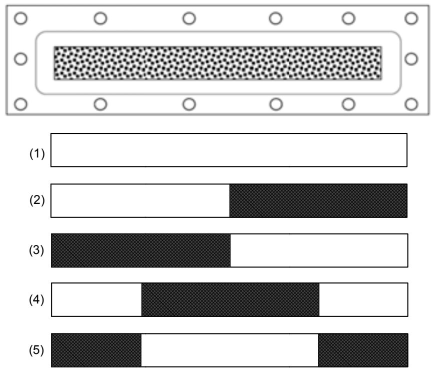
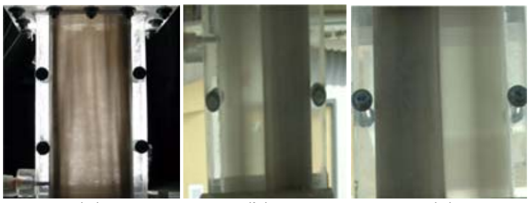


Figure 2. Structure of the distributor and medal slice design. (1) fully opened; (2) left-opened; (3) right-opened; (4) sides opened; (5) center opened



(a) (b) (c)

Figure 3. Pictures of flow structure: (a) Fully opened; (b) Left opened; (c) Right opened

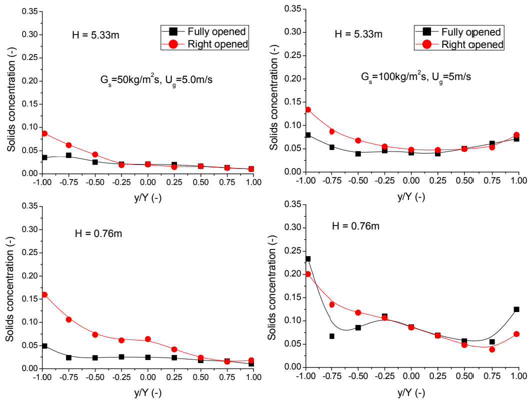
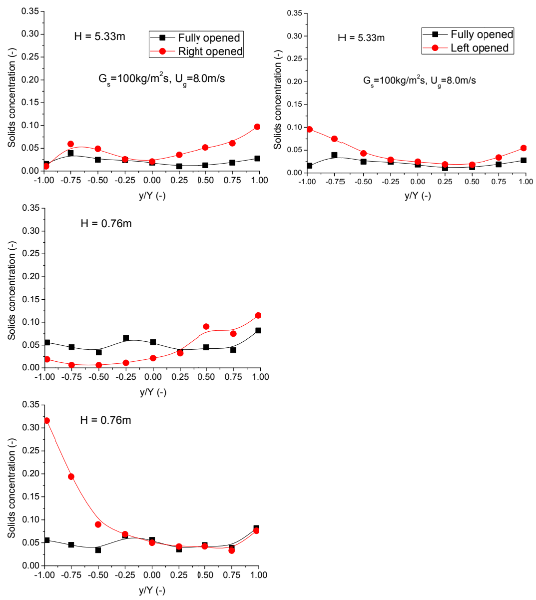
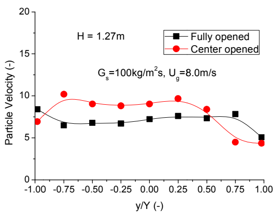


Figure 5. Profiles of solids concentration (Right opened)



(a) (b)

Figure 4. Profiles of solids concentration (a) Left opened; (b) right opened



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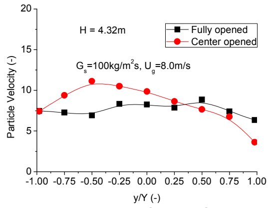
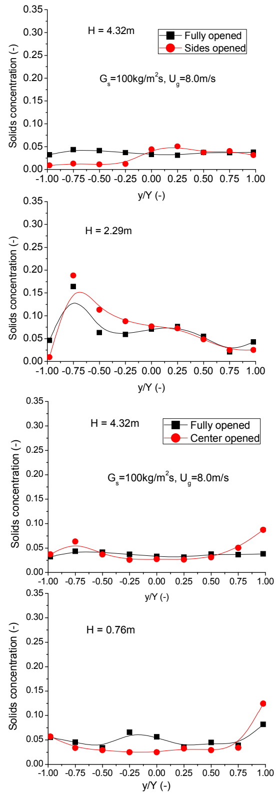
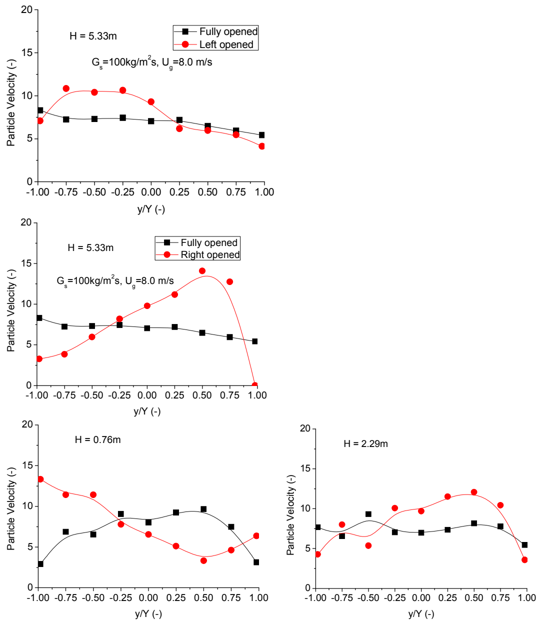


Figure 7. Profiles of particle velocity (Center opened)



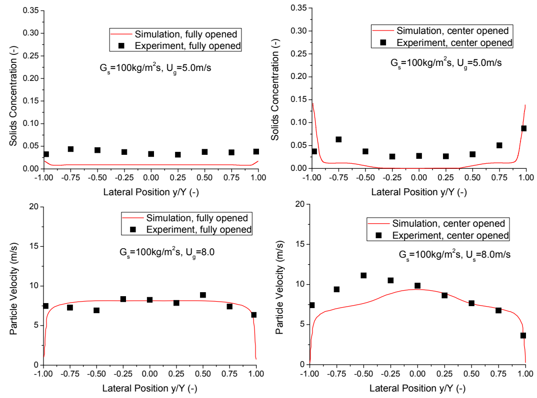
(a) (b)

Figure 6. Profiles of solids concentration
(a) Sides opened; (b)center opened



(a) (b)

Figure 8. Profiles of particle velocity
(a) Left opened; (b) right opened



(a) (b)

Figure 9. Experimental and simulated profiles
of solids concentration and particle velocity
(a) fully opened; (b) center opened)