EFFECT OF RING BAFFLE CONFIGURATION ON SYSTEM MIXING IN RISER OF CIRCULATING FLUIDIZED BED REACTOR BY USING CFD SIMULATION AND FACTORIAL EXPERIMENTAL DESIGN ANALYSIS

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Abstract: The inappropriate gas-solid mixing in a circulating fluidized bed riser is now an important problem for this type of chemical reactor. The solid distribution inside the system is not uniform across the system and needs to be adjusted to improve the reaction conversion efficiency. Therefore, the aim of this study is to explore the effect of ring baffle configuration parameters (baffle opening area, space between baffles, baffle thickness, numbers of baffle, uniformity of space between baffles) on system mixing in a riser of circulating fluidized bed reactor by using computational fluid dynamics (CFD) commercial program, ANSYS Fluent 6.3.26. To interpret the parameter effect, the systematic statistical theory, factorial experimental design analysis, was selected to use. The simulation results showed that the ring baffle configuration had a significant effect on the fluidization hydrodynamics and gas-solid mixing. From the analysis of variance methodology, baffle opening area, space between baffles, and interaction between baffle opening area-space between baffles were the parameters that affected the system mixing. Between all of these parameters, interaction between baffle opening area-space between baffles was the key parameter. In addition, a regression model for predicting the gas-solid mixing was obtained. By comparing the solid concentration or volume fraction distributions in radial system direction, most of the riser with baffle showed more flat profile than the riser without baffle. This means that the ring baffle improves the system mixing in radial direction and eliminates the backflow near the wall which showing benefit for the heat and mass transfers in this circulating fluidized bed reactor system.

1. Introduction

Circulating fluidized bed reactors (CFBR) have been widely employed in many commercial industry applications because of their advantages, such as being a continuous process coupled with high throughput of gas and solid particles and being a highly effective reactor for fast multiphase chemical reaction systems. However, it also has distinct disadvantages such as the non uniform solid distribution and solids back mixing phenomena inside the system that can strongly decrease the conversion and selectivity [1-3]. Because of these problems, the performance of this reactor needs to be adjusted. Internal adding is the interesting way to improve the hydrodynamics and mixing inside the system. For example, Jiang et al. [4] investigated the baffle effects on performance of ozone decomposition circulating fluidized bed reactor by using the FCC particles with a mean diameter of 89 μm impregnated with ferric oxide as system catalyst. It was found that, except at the lowest gas velocity, their riser with baffles yielded a higher solid hold up and ozone conversion in the gas phase than that without baffles. The reason is because baffles could enhance gas-solid contact efficiency by promoting radial gas and solid mixing under high gas velocity conditions.

The aim of this study is to explore the effect of ring baffle configuration parameters (baffle opening area, space between baffles, baffle thickness, numbers of baffle, uniformity of space between baffles) on system mixing in a riser of circulating fluidized bed reactor by using computational fluid dynamics simulation and factorial experimental design analysis.

2. Materials and Methods

2.1 System description and computational domain

In this study, the results from Particulate Solid Research, Inc. (PSRI) challenge problem I [5] was chosen as the reference case to validate the numerical results. Their riser diameter (D) and height (h) were 0.2 m and 14.2 m, respectively. The particles in their system were FCC particles with 76 μm diameter and 1,712 kg/m^3 density (Geldart group A particles).

The studied system was operated in the cold flow condition. The riser configuration is shown in Figure 1 (a). The gas inlet was fed to the system at the bottom of the riser with the input velocity of 5.2 m/s. The particles were fed from the two side-inlets at 0.3 m above the bottom of the riser with a width of 0.1 m. The solid input velocity was 0.476 m/s with a solid volume fraction of 0.60. The gas and solid exited through two symmetric side outlets at 0.3 m below the top of the riser with a width of 0.1 m. The fluidization regime in this system was fast fluidization regime.

For baffle configuration, five factors were investigated in a 2^{5-1} design with the objective for improving the system mixing. The five factors were A = baffle opening area (50% and 75%), B = space between baffles (0.08 m and 0.20 m), C = baffle thickness (0.01 m and 0.04 m), D = numbers of baffle (5 and 14) and E = uniformity of space between baffles (1 and 1.25). The modified riser configuration with baffles is shown in Figure 1 (b) and the construction of the 2^{5-1} design is summarized in Table 1. The maximum and minimum parameter values that used in this study were covered the widely used value in the commercial units [6]. In the following sections, the base case condition which was the riser without baffle was abbreviated as “BF”.

This study used a two dimensional model for the simulation because a three dimensional model requires long computation time. For approximation of the two dimensional riser to simulate the three dimensional riser, the two inlet-outlet design is needed. This was done because a one inlet-outlet design for the two dimensional riser could not capture the realistic mixing throughout the riser height [7-8]. The computational domain of the riser used in this study was 6,000 computational cells. The used time step was 1×10^{-3} s. The simulation was conducted for 40 s of simulation time.

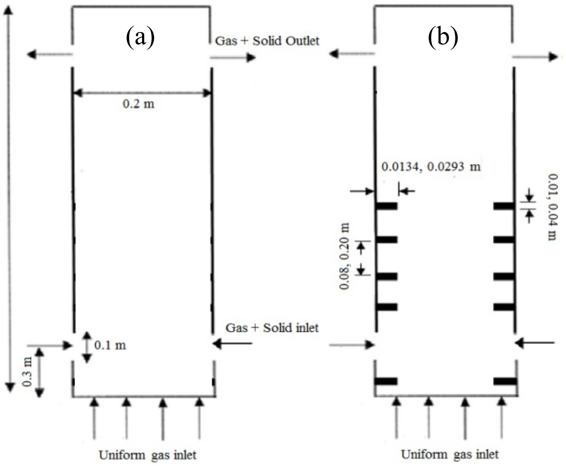


Figure 1. Configurations of base case (a) and modified circulating fluidized bed reactor with ring baffles (b).

2.2 Mathematical model

Currently, there are no universal mathematical for predicting the performance of circulating fluidized bed reactors. For the gas-solid two-phase flow, the widely used numerical models are the Lagrangian model and the Eulerian model. In this study, the Eulerian multiphase model was selected. Then, a set of governing equations, which were mass and momentum conservation equations for each phase, with constitutive equations were solved. The equations used in this study were based on the kinetic theory of granular flow [9] and the energy minimization multi-scale (EMMS) drag model. The EMMS drag model has been proved to be an effective way for modeling a high solid mass flux system of FCC particles [8]. This study used the commercial CFD program FLUENT 6.3.26 for modeling the system. According to the reference case, there had not been enough information given on the values of modeling parameters which were the restitution coefficients and the specularity coefficient. Some adjustment process of these values, as well as the grid independent study, thus had been done to find the suitable condition that matches with the experimental data and to obtain optimized parameter values.

3. Results and Discussion

To study the baffle effects on system mixing, the standard deviation of radial solid volume fraction was used as the response variable in factorial experimental design analysis.

Table 1: The construction of the 2^{5-1} design and their corresponding standard deviation of solid volume fraction in radial direction results.

Case	A	B	C	D	E=ABCD	SD
BF	-	-	-	-	-	0.0405
1	75%	0.08	0.01	5	1.00	0.0360
2	50%	0.08	0.01	5	1.25	0.0464
3	75%	0.20	0.01	5	1.25	0.0423
4	50%	0.20	0.01	5	1.00	0.0358
5	75%	0.08	0.04	5	1.25	0.0369
6	50%	0.08	0.04	5	1.00	0.0376
7	75%	0.20	0.04	5	1.00	0.0405
8	50%	0.20	0.04	5	1.25	0.0343
9	75%	0.08	0.01	14	1.25	0.0398
10	50%	0.08	0.01	14	1.00	0.0396
11	75%	0.20	0.01	14	1.00	0.0451
12	50%	0.20	0.01	14	1.25	0.0311
13	75%	0.08	0.04	14	1.00	0.0424
14	50%	0.08	0.04	14	1.25	0.0375
15	75%	0.20	0.04	14	1.25	0.0382
16	50%	0.20	0.04	14	1.00	0.0315

From the table, it can be seen that most of the case which installed baffles had lower standard deviation of radial solid volume fraction than the base case. This means that the solids are more uniformly distributed. This enhances the system mixing because the down falling solids due to the gravity force are broken apart into small clusters by baffles. The baffle not only reduces the downward particle motion, but also promotes the turbulent gas flow. The eddies around the baffles can push the solids at the wall back to the core region, therefore, increase the mixing of solid in radial direction in the riser.

From all the results, case 12 had the lowest standard deviation of solid volume fraction in radial direction which was 0.0311. This is probably due to the small baffle opening area that reduces the solid back-mixing and more space between baffles which promotes the interior recirculation. Comparing with case 2 which has the same baffle opening area but has less space between baffle, it will decrease the system recirculation and give more chance for particle cluster occurrence at the wall region.

Table 2: The analysis of variance for 2^{5-1} design.

Source	Sum of Squares	DF	Mean square	F_0	p-value
A	$4.68x10^{-5}$	1	$4.68x10^{-5}$	5.45	0.05
B	$1.91x10^{-5}$	1	$1.91x10^{-5}$	31.41	0.19
AB	$9.73x10^{-5}$	1	$9.73x10^{-5}$	11.85	0.01
Error	$1.20x10^{-4}$	12	$9.97x10^{-6}$		
Total	$2.83x10^{-4}$	15			

Table 2 summarizes the analysis of variance for 2^{5-1} design in this study. The two factors, baffle opening area (A) and baffle opening area-space between baffles interaction (AB), were the parameters that affected the system mixing. This was indicated by the lower value of p-value than 0.05. However, from the experimental design theory, if the interaction of AB is a significant effect, their first order effects, A and B, have to be considered even when their p-values are higher than 0.05. Then, the regression coefficients can be obtained from each effect estimates. The regression model for predicting the standard deviation of solid volume fraction in radial direction (Y) is:

$$Y = 0.038+0.0017X_A-0.0011X_B+0.0025X_AX_B$$

where X_A,X_B,$X_AX_B$are coded variables that correspond to the factors A , B and the AB interaction.

Figure 2 (a) shows the positive effect of baffle opening area (A) and negative effect of space between baffles (B). When the baffle opening area is increasing or space between baffle is decreasing, the standard deviation of solid volume fraction in radial direction will increase which lowers the system mixing.

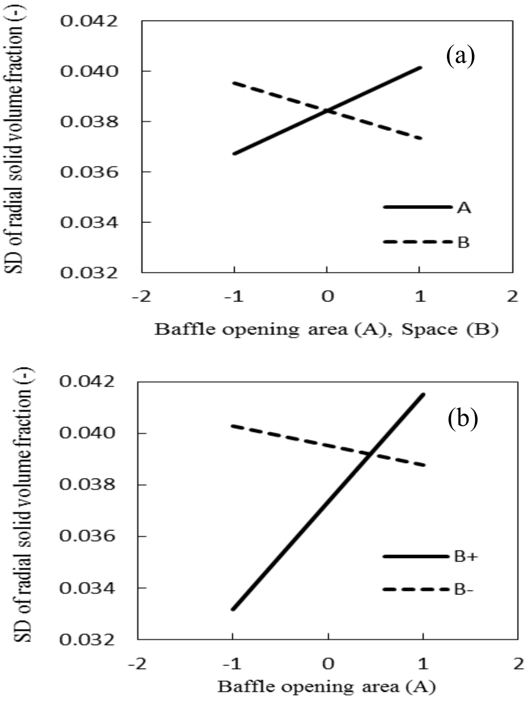


Figure 2. The main effect plot (a) and interaction effect plot (b).

The AB or interaction baffle opening area-space between baffles is plotted in Figure 2 (b). This plot showed higher slope of AB when comparing with the main effect plot. The graph sensitivity indicates that the interaction effect is higher than the main effect which is consistent with the analysis of variance.

Since there were many result cases, case 2 and 12 were selected to show with the base case. This is because these two cases were the lowest and highest system mixing cases, respectively. All the results were time-averaged after they reached steady state condition.

The solid volume fraction profiles in radial system direction are plotted in Figure 3. It showed that the radial particle distribution was effectively improved by placing ring baffle as shown by case 12 configuration. Case 12 had the best configuration which lowest standard deviation of solid volume fraction in radial direction as can be seen in Table 1 or can be indicated by more flat solid volume fraction profile than the other cases. This is because of the interruption of the gas-solid flow field. Also, case 12 configuration suppresses solid back-mixing as can be observed by the lower solid volume fraction at the wall region than the other configurations.

The radial solid velocity profiles in radial system direction are illustrated in Figure 4. Case 12 showed the highest radial solid velocity profile near both of the riser wall regions. This makes more system solid to move into the core region as can be observed in Figure 3. It will reduce the particle cluster at wall region and improve the radial gas-solid mixing. Case 2 was the worst configuration. The radial solid velocity profile was undirectional which is consistent with the solid volume fraction profile. This promotes agglomeration of solids which lowers the system mixing.

The axial solid velocity profiles in radial system direction are depicted in Figure 6. This plot exhibited that case 12 had lowest particle falling downward near the wall region while the base case and case 2 show more particle falling downward. It implies that case 12 has lower solid back-mixing than the other cases due to the reduction of the non-uniform core-annulus system flow structure. As already discussed, this is because case 12 has low baffle opening area and high space between baffle.

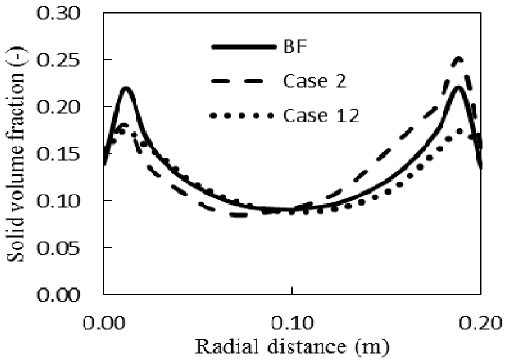


Figure 3. The solid volume fraction profiles in radial system direction.

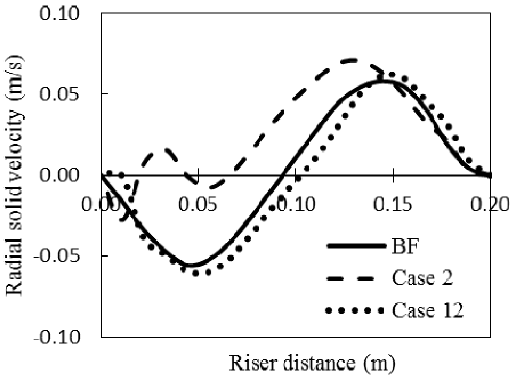


Figure 4. The radial solid velocity profiles in radial system direction.

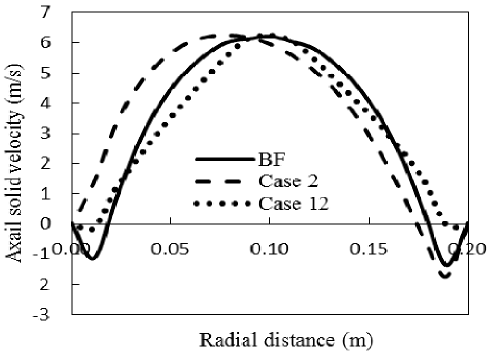
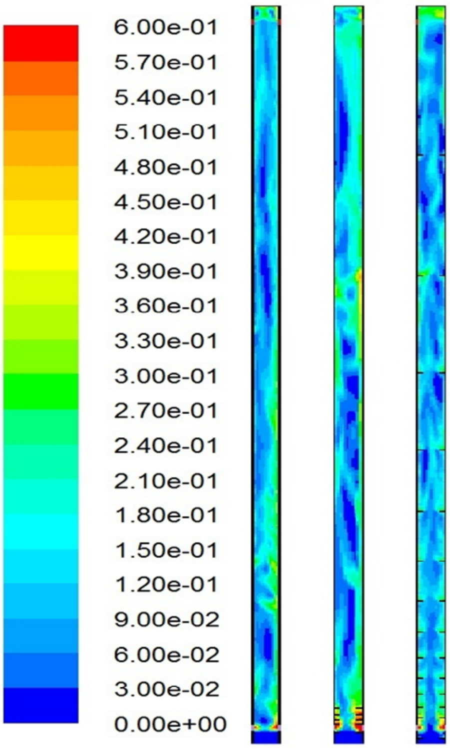


Figure 5. The axial solid velocity profiles in radial system direction.



(a)
BF

Figure 6. The instantaneous contour plots of solid volume fraction at 30 s.

The instantaneous contour plots of solid volume fraction at 30 s for case 2, 12 and base case are shown in Figure 6. It can be seen that the solid volume fraction in case 12 was more homogeneous along the riser column than base case and case 2, respectively. In case 12, most of the solids flew upwards at the central region and only few solids flew downwards at the wall region. This is because solid back-mixing is prevented by the ring baffle configuration. In the base case and case 2, higher downward solid flows were observed. These make the systems to be more heterogeneous.

4. Conclusion

From the computational fluid dynamics, the ring baffle configuration has an effect on the fluidization hydrodynamics and gas-solid mixing. The ring baffle improves the system mixing in radial direction and eliminates the backflow near the wall which showing high benefit for the heat and mass transfer in this reactor system. From the analysis of variance, the baffle opening area, the space between baffles and the interaction between baffle opening area-space between baffles were the important parameters that had an effect on the system mixing. Between all of these parameters, interaction between baffle opening area-space between baffles was the key parameter. In addition, a regression model for predicting the gas-solid mixing was obtained for further using in the designing stage of circulating fluidized bed reactor.

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