Numerical simulation of gas-solid two-phase flow in U-beam separator

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Abstract. Numerical simulation is carried out for gas-solid two-phase flow in a U-beam separator. In this study, the U-beam is altered with the inlet fins in order to improve the performance of the separator. The inlet fin angle of the separator are 30°, 35°, 40°, 45°, 50°, 55°, and 60°. The governing equations are the Reynolds-Averaged Navier-Stokes equation with the standard k-ε model and the discrete phase model (DPM) describing the discrete two-phase flow as well as stochastic tracking model. Results show that the pressure drop deviation with fins is within 3% from those without fins. It is found that there is a maximum separation efficiency at the fin angle of 35°. Fin induces generation of a stagnation region which could collect particles and lead to change of vortical structures. The fin induced flow also causes the turbulent intensity inside the baffle to decrease to facilitate separation.

1. Introduction

The inertial separator is an apparatus to separate particles from gas, which relies on the difference of inertial force between gas and particles [1]. In the early years, a Swedish corporation introduced the U-beam separation technique for circulating fluidized bed boilers (CFBB) and later the U-beam separation was adopted by B &W Corporation [2]. In 1994, Ogawa put forward an inertial separation device manufactured with angle iron in his monograph [3].

A few research groups have also done a lot of works on it, for example: Xi'an Jiaotong University presented an impact type inertial separator with fluted tubes [4]; Zhejiang University developed a finned tubes impact gas-solid separator with heat transfer enhancement effect [5]; Tsinghua University has developed a combined multiple-channel inertial separator [6-7]. Besides, Cen et al. developed Fluctuation-Spectrum-Random-Trajectory Model [8]. Wang et al. used Reynolds Stress Model, taking into account the collision of particles and wall, to simulate inertial separator [9]. Li et al. investigated the influence of different structure parameters on the U-beam separator by using the discrete phase model, in which the solid phase is defined as discrete phase [10].

In this paper, the traditional U-beam separator is studied using numerical simulation method, and the separation efficiency is compared with experimental data to verify the reliability of computing. Then, the traditional U-beam separator is altered with inlet fins, and the effect of inlet fins on the performance of U-beam separator is analyzed.

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2. Computing method and physical model

2.1. Computing method

In this research, since the volume fraction of solid particle is small, it is assumed that the gas is continuous phase and the solid particle is discrete phase. The governing equation for gas phase is the Reynolds-averaged Navier-Stokes equations, while the discrete phase model (DPM) is used for the solid phase. What’s more, the discrete random walk (DRW) model is adopted to predict the dispersion of the particles due to turbulence, which determines the instantaneous gas velocity.

2.2. Physical model

For simulation of U-beam separation, the streamwise, wall-normal and spanwise directions are in x, y and z directions, respectively. The computational domain size \((L_x \times L_y \times L_z)\) is \(1.2 \times 1.0 \times 0.5\), whose unit is m. For single U-beam, its length and width are both 0.04 m, while the thickness is 0.003 m. Four rows of baffles are fixed 0.5 m apart from the entrance in a staggered formation, while the transverse and longitudinal spacing are both 0.04 m.

The modification of the traditional U-beam separator structure is as follow. Fins are added at the inlet of the baffle, whose length is 0.01 m. An angle between the fin and the inner wall of the baffle is called fin angle \(\alpha\). To investigate the effect of fin, several cases are studied. The inlet gas velocity equals to 4 m/s and 10 m/s, while \(\alpha\) is 30°, 35°, 40°, 45°, 50°, 55° and 60°. For the two-phase flow studied, the particle concentration is 0.025 kg/m³.

The boundary conditions are as follow. The velocity at inlet is given, and gradient condition is given at the outlet. Symmetrical boundary condition is employed at centerline. On the wall boundary, non-slip conditions are used for the three velocity components. When calculating two-phase flow, the bottom wall is defined as “trap”, inlet and outlet surface are defined as “escape”, and other walls are defined as “reflect”.

2.3. Model Validation

To verify the accuracy of simulation result, the simulation results are compared with experiment [10]. The solid particle is silica sand with a diameter of 220–1000 \(\mu\)m and density of 2650 kg/m³. Figure 1 plots the separation efficiency. The numerical results produce a good agreement with experimental data, thus proving the reliability of numerical simulation.

As it is seen, when inlet velocity increases, the separation efficiency decreases rapidly because the drag force acting on the particles increases. As such, the particles are not easily deviated from the gas, and therefore are easier to be re-entrained because of colliding inside the baffle.
3. Results and analysis

3.1. Effect of fins on performance of U-beam separator

Table 1 shows the pressure drop of U-beam separator under different fin angles. As the fin angle $\alpha$ increases, the pressure drop follows a downward trend. The maximum deviation of pressure drop between the U-beam separator with fins and the traditional U-beam separators is within 3%. Furthermore, “SQ” stands for the square-shape baffle of traditional U-beam separator (without fins).

| $v$ (m/s) | $\alpha$ | None | 30° | 35° | 40° | 45° | 50° | 55° | 60° | Max deviation |
|-----------|----------|------|-----|-----|-----|-----|-----|-----|-----|---------------|
| 4         |          | 198.4| 201.8| 200.2| 200.1| 200.5| 200.1| 198.6| 197.5| 1.7%          |
| 10        |          | 1236 | 1256.4| 1267.3| 1246.8| 1249.3| 1245.8| 1237.4| 1230.2| 2.5%          |

Figure 2 shows the separation efficiency under different fin angles and the particle size range is 60~200 $\mu$m. For the velocity of 4 m/s, the separation efficiency of all seven fin angles has been enhanced, especially at 35°. Compared with the result of traditional type, an improvement of 8~13% is achieved for the case of 35° fin angle. However, for the velocity of 10 m/s, an improvement of 2~4% is achieved for the case of 35° fin angle.

To make further analysis of fin’s effect on the separation efficiency, the bottom wall is divided into six zones signed as trap 0~5 as displayed in figure 3.

![Figure 3. Partition of bottom wall and enlarged view of the cut piece.](image)

Figure 4 shows the separation efficiency for two cases, which are U-beam separator with fins at $\alpha$=35° and traditional U-beam separator. The separation efficiency of the former is 2~3 times of the latter in trap 1 with particle diameter of 60~120 $\mu$m. However, both the two separators show similar properties in other trap zones. When the particle size is larger than 120 $\mu$m, the separation efficiency of U-beam separator with fin angle of 35 improves significantly in trap 1 and trap 2, while in other trap regions their difference is not obvious.

3.2. Analysis of flow characteristics

A rectangular zone is cut from the cross section $y=0.5$ m as shown in large view in figure 3. It gives more details of the region whose length and width is 0.09×0.08 m, including half of the injection and collection area from top view. The distributions of the turbulence intensity, velocity and particle concentration are shown in figures 5 to 7 for three configurations, which are U-beam separator with fins at $\alpha$=35°, $\alpha$=50° and the traditional U-beam separator. In these figures, parameters are plotted at five locations of $x$ at 0.45, 0.48, 0.5, 0.51 and 0.53 m.
At five positions mentioned above, the velocity distribution has no significant difference for the three configurations as displayed in figure 5. However, the velocity at above mentioned five locations for fins at $\alpha=35^\circ$ and $50^\circ$ cases approach to zero earlier than the traditional type at $x=0.5$ m. Meanwhile, a negative streamwise velocity appears, indicating backflow inside the baffle.

Figure 6 plots the turbulent intensity, which is defined as $I = (2/3-k)^{1/2}/\pi$. It can be seen that the turbulent intensity of the three cases at the position $x=0.45$ m is almost the same. However, the turbulent intensity shows violent fluctuation with the increase of x value. The flow for cases at $\alpha=35^\circ$ and $50^\circ$ always tends towards to be stable earlier throughout the region, and inside the baffle the turbulent intensity for traditional U-beam separator is higher than those with fins.
The researches on turbulent diffusion in [8] show that smaller particles diffuse faster than larger particles in gas, and diffusion enhances when the turbulence intensity of gas flow increases. For this reason, turbulence intensity can to some degree indicate particle’s following ability with gas.

Furthermore, there forms a stagnation region between the fin and the inner wall of baffle where the velocity is very close to zero as seen in figure 7. Meanwhile, turbulent intensity is very low in this region seen from figure 6(d). This is because when the gas flow is obstructed by fins, the particles, especially for small particles, are easier thrown into the stagnation region with the action of centrifugal force. Figure 7 shows that the particle concentration in stagnation region is significantly higher than other regions. Particles are difficult to escape from stagnation region and then separate from the gas eventually, thus enhance the separation efficiency of the U-beam separator.
4. Conclusions
Numerical simulation has been carried out to study the flow characteristics of U-beam separator. Results show that the separation efficiency of U-beam separator can be enhanced by fins added at the inlet of the baffle. The maximum separation efficiency is obtained at the fin angle of $35^\circ$. It is also found that the pressure drop of U-beam separator with fins has not been affected largely by fins, as the maximum pressure drop variation is within 3% from the traditional U-beam separator to the U-beam separator with fins. The separation efficiency could be increased by 13% at inlet velocity 4 m/s. At inlet velocity 10 m/s, there is still 4% increase of separation efficiency for fin angle of $35^\circ$. Simulation results indicate that fin induces generation of a stagnation region which could collect particles and lead to change of vortical structures. The fin also causes the turbulent intensity inside the baffle to decrease which helps separation. These influences play important roles in the separation efficiency improvement.

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References
[1] Che D F and Li H X 2007 Multiphase Flow and its Application (Xi’an: Xi’an Jiaotong University Press) 361 (in Chinese)
[2] Belin F and Flynn T J 1991 Proc. of the 10th International Conference on FBC (San Francisco, USA, 30 April - 3 May, 1989) 2 287-94
[3] Ogawa A 1984 Separation of Particles from Air and Gases (CRC press)
[4] Zhang Y Z, Li Y L, Zhang X M, Jin D A, Duan J Z, Bao D W and Wang G H 1989 Power Eng. 9(6) 9-13 (in Chinese)
[5] Chen K F, Li X D and Li Y X 1997 Chemical Eng. J. 66 159-169 (in Chinese)
[6] Zhang X 1988 Horizontal flow separator with two-stage inertia separation. China CN87103655 (in Chinese)
[7] Zhang X 1987 Fluidized-bed boiler. China CN85109455 (in Chinese)
[8] Cen K F 1999 The Theories and Technologies of Gas-Solid Separation (Hangzhou: Zhejiang University Press) (in Chinese)
[9] Wang H G, Liu S and Jiang F 2004 Journal of Engineering for Thermal Energy and Power. 19(4) 380-83 (in Chinese)
[10] Li H W, Liu J J, Liu J, Han H B and Li N 2012 Int. Workshop on Information and Electronics Eng. (IWIEE), Procedia Eng. 29 3227-33
[11] Li H W, Han H B, Wang J and Zhang H 2011 Acta Armamentarii 32(2) 225-29 (in Chinese)
[12] Tan X J, Chen L H and Li H J 2005 Journal of Hydrodynamics. Ser A 20 910-15
[13] Baskakov A P, Mudrechenko A V, Bubenchikov A M, Starchenko A V, Gogolev A F and Markovich D M 2000 Powder techno. 107 84-92