CFD Simulation Study on Particle Arrangements at the Entrance to a Swirling Flow Field for Improving the Separation Efficiency of Cyclones

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ABSTRACT

Based on the concept of particle arrangements at the entrance of a swirling flow field, this paper designs common cyclone (C-cyclone), positive rotation cyclone (PR-cyclone), and reverse rotation cyclone (RR-cyclone). FLUENT software is used to perform CFD (computational fluid dynamics) simulation study on these three cyclones. The study result shows that particles are more easily separated if they are closer to the lower part of the outer wall of the entrance to the swirling flow field, whereas particles access the short circuit current more easily if they are closer to the upper part of the inner wall, thereby generating particles escape. The RR-cyclone helps particles to avoid regions of short-circuiting flow, and thus improves the separation performance. In each part of the separator, the particle concentration within the RR-cyclone is lower than that in the C-cyclone and in the PR-cyclone. Moreover, the separation efficiency of the RR-cyclone is higher than that of the C-cyclone and the PR-cyclone in different inlet flows.

Keywords: Cyclone separator; Particle arrangements; Computational fluid dynamics (CFD).

INTRODUCTION

Solid or liquid particles, with diameters between a few nanometers and several thousand micrometers, are suspended in the air or in industrial gases to varying degrees. Since the 1980s, people have realized the increase in particle concentration in aerosols, particularly the increase in particulate matters (PM_{2.5}) with equivalent diameters less than 2.5 µm in aerosols, which will have a severe impact on the human health. As an important method for capture separation and recycle fine particles, cyclone separation is characterized by a great processing capacity as easy operation and maintenance, low cost, safety, and reliability. It is widely used in the fields of gas purification, environmental processing, chemical production, resource exploration, automotive manufacturing, and other industries.

In recent years, many scholars used experimental methods in combination with numerical simulation methods study the separation performance of cyclone separators (Saltzman et al., 1983; Kuo et al., 2001; Yoshida et al., 2001; Asbach et al., 2011; Wu et al., 2014; Xiong et al., 2014). Cortes and Gil (2007) studied the modeling of gas and particle flow inside cyclone separators. Ng et al. (2007) investigated the flooding, re-entrainment and grade efficiency in axial flow cyclones. Tsai et al. (2004, 2007) used an axial flow cyclone to remove nanoparticles at low pressures or vacuum conditions. Chen et al. (2007), Hsa et al. (2005), and Tsai et al. (2008, 2011, 2012) applied a modified axial flow cyclone to assess the exposure of nano-sized and respirable particles at different workplaces. Zhao et al. (2004, 2005) studied the different inlet configurations of a cylinder-on-cone cyclone. Zhao et al. (2010, 2012) predicted the cylinder-on-cone cyclone separation efficiency and pressure drop by developing two different models. Su and Mao (2006) used a three-dimensional particle dynamics analyzer to study the flow in a square-shaped cyclone separator that was designed for large circulating fluidized bed application. Similarly, Su et al. (2011a, b) and Diao et al. (2009) studied the numerical simulation of the effect of inlet and exhaust configuration on a square-shaped cyclone. Lin et al. (2013) designed a high-efficiency wet electro-cyclone for removing fine and nanosized particles. Molina et al. (2008) carried out a detailed experimental investigation on the novel GLCC for low and high pressure conditions. Ma et al. (2013, 2014a, b) studied cyclone device and applied it in hydrogenation unit and ethylene plant. Quan et al. (2009, 2010) designed a newly gas liquid water-sparged aerocyclone reactor and applied it in wastewater treatment.

With the gradual in-depth study of cyclones, more scholars...
have started to pay attention to a series of butterfly effects caused by the position change of particles at the entrance to the swirling flow field. Wang et al. (2006) found that the initial position of particles at the cross section of the entrance has a very important impact on the tracks of particles in the separator, thus affecting the separation of particles; Liu et al. (2008) determined the pre-sedimentation effects of particles by introducing a spiral structure at the entrance of the swirling flow field, which effectively improved the separation efficiency for small particles; Hsieh and Rajamani (1991) studied the tracks of different particles at the same position conditions of the entrance; Bamrungsri et al. (2008) measured the separator with only one section from the positions of different particles at the entrance by using high-speed camera technology; and Yang et al. (2013) performed a simulation study on the changes in the pressure and concentration of flow field caused by the changing position of the particles at the entrance.

Based on the different positions of particles at the entrance of the swirling flow field, this paper designs the common cyclone (C-cyclone), the positive rotation cyclone (PR-cyclone), and the reverse rotation cyclone (RR-cyclone). In the C-cyclone (Fig. 3), the particles diameter at the entrance show a disordered state, whereas the particles diameter was in descending and ascending order from the outer wall to the axis in the PR-cyclone (Fig. 4) and in the RR-cyclone (Fig. 5), respectively. Based on a CFD simulation study, the influencing results of particle arrangement law, concentration distribution, and separation performance after being arranged are obtained. This paper not only develops a kind of cylinder cone cyclone that can enhance separation efficiency but also provides a reference for the improvement of the separation efficiency of other types of cyclone separator.

**METHODS**

With the rapid development of the computer operating capability, CFD simulation has obtained significant advantages in describing the fluids with turbulent flow; thus, it has become one of the important methods for studying cyclone separation. Therefore, the design and construction of CFD simulation of sorting-type cyclone separator is a kind of economic and effective study approach.

We designed a 75-mm-diameter particle arrangement device and a 75-mm-diameter cylinder cone cyclone. Figs. 1 and 2 show their model structures, and the detailed dimension is shown in Table 1. Particle arrangement device do not take effect for particle separation, it only moves particles radially depending on their inertia. The distance between the axis of cyclone and the axis of particle arrangement device was 200 mm.

The multiphase flow in a cyclone is quite complicated. In this work, the separation efficiency and particle concentration fields of the cyclone were numerically simulated using FLUENT 6.3.26 computational fluid dynamics (CFD) software. The cyclone separation process belongs to the class of two phase three-D strong vortex turbulent flows. The Reynolds Stress Model (RSM) considers streamlined bending, vortex, rotation, and rapid tension change, more

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strictly. Complex flow has a higher accurate prediction potential, so it is suitable for strong turbulence simulation in a cyclone. The simulated particle separation efficiencies approximately agree with the available experimental data. As such, we chose RSM to simulate the continuous flow field in a cyclone. We adopted the particle stochastic trajectory model to track the particle trajectories and the separation process. In the CFD simulation, RSM model was selected to simulate the continuous phase, meanwhile, DPM (Discrete Phase Model) model was chosen to simulate the disperse phase.

We did the simulation for the C-cyclone, the PR-cyclone, and the RR-cyclone. The numerical simulation is based on the finite difference method started at the inlet. The key point is to establish the mixing non-structure grid system. By using the Gambit method to generate a grid and perform independence calculation, we obtained three cyclones grid models, as shown in Figs. 3–5. During the simulation calculation, the gas phase is air and the temperature is normal. To close the actual application, we further consider the slurry conveyor of the outlet. The pressure outlet boundary conditions are used. The inlet flows are $30 \text{ m}^3\text{ h}^{-1}$, $40 \text{ m}^3\text{ h}^{-1}$, $50 \text{ m}^3\text{ h}^{-1}$, $60 \text{ m}^3\text{ h}^{-1}$, and $70 \text{ m}^3\text{ h}^{-1}$. The inlet and outlet boundary conditions of the particle phase are set as fully escapable, and the wall is set as reflection surface. The solid phase import boundary condition is the condition where we set the jet source of particle import as a non-point source. Particles are uniformly distributed on the grid of the whole import section, and particles are injected from the center of each grid. The inlet speed of the particles is set equal to that of flux gas. The inlet particle sizes are $0.1–30 \mu\text{m}$ and their density is $2.1 \text{ g cm}^{-3}$.

RESULTS AND DISCUSSION

The Effect of Particle Arrangement on the Trajectory

As shown in Fig. 6, 16 grids with the same area are obtained by quartering the width and height of the section at the entrance of the separator. Figs. 7, 8, and 9 show the corresponding tracks of $0.3, 0.6,$ and $1 \mu\text{m}$ diameter particles after being filled in 16 grids when the flow through the separator is $40 \text{ m}^3\text{ h}^{-1}$. The particle tracks have greater
similarity: from the outer wall of the entrance section to the inner wall, the particles closer to the outer wall are more easily separated from the particle outlet, and from the upper to the lower of the entrance section, the particles closer to the lower part are more easily separated from the particle outlet. A particle can move to the conical section; all of them may be separated from the particle outlet. When the particles are close to the axis in the cylinder, there is a probability of going into short circuit flow or returning to upstream flow to gas outlet and escape. The particles close to the upper entrance section always go into the separation blind zone of short-circuit current, and they are difficult to be separated from the particle outlet, with very short tracks, and short-circuit current is easily generated.

Comparing with the separation of the same particle size, the particles filled in the outer wall of entrance section have less number of turns or tracks than the particles filled near the inner wall. As shown in Fig. 7, 24 is shorter than 23, 34 is shorter than 32 and 33, 44 is shorter than 41, 42, and 43 in the track; in Fig. 8, 24 is shorter than 22 and 23, 34 is shorter than 32 and 33, 44 is shorter than 41, 42, and 43 in the track. In Fig. 9, 24 is shorter than 21, 22, and 23; 34 is shorter than 31, 32, and 33; 44 is shorter than 41, 42, and 43 in the track.
Fig. 7. The particle track of Number 11–44 (Q = 40 m$^3$ h$^{-1}$, d$_p$ = 0.3 μm).

Fig. 8. The particle track of Number 11–44 (Q = 40 m$^3$ h$^{-1}$, d$_p$ = 0.6 μm).
Comparing with the separation of the different particle sizes, the larger particles will undergo the greater centrifugal force; hence, they are easily separated, and the effect of the position of entrance section will be smaller. When the particle size is 0.3 µm, the particles at position 22# cannot be separated, but they can be separated if the particle size is 0.6µm. If the particle size is 0.6µm, the particles at positions 21# and 31# cannot be separated, but they can be separated when the particle size is 1 µm. At three different particle sizes, the particles at positions 11#, 12#, and 13# escaped through the gas outlet, instead of being separated, which indicates that the effect of the short-circuit current at the upper part of the entrance section is independent of particle size. Moreover, separating the particles when they are at the upper right part of entrance section (above the diagonal in Fig. 6) is difficult; separating the particles is easier when they are at the lower left part of the entrance section (below the diagonal in Fig. 6).

**Effect of Particle Arrangements on Concentration Distribution**

Fig. 10 shows the concentration distribution cloud picture of C-cyclone, PR-cyclone, and RR-cyclone at X-Y section and at seven X-Z sections after the addition of the hybrid particle swarm at a flow of 40 m³ h⁻¹. The hybrid particle swarm consists of 0.1, 0.3, 0.5, 1, 1.5, 3, 5, 10, 15, 20, and 25 µm-diameter particles with equivalent masses. The concentration of the particles in the air is 20 mg L⁻¹. The upper plane at the entrance of the separator is defined as Z0. One section is set in every 50 mm, with a total of seven sections, that is to say, the distances to Z0 section are: Z1 = 50, Z2 = 100, Z3 = 150, Z4 = 200, Z5 = 250, Z6 = 300, and Z7 = 350.

From the distribution at the X-Y section, the concentration in the extending area of the gas outlet is far lower than that in the area near the edge of the wall; the concentration in the conical area is far lower than that in the cylinder, and the concentration in the lower part of the conical area is lower than that in the upper part, which indicates that the majority of particles are captured by the wall in the cylinder and the upper part of the conical section. From the comparison of the three separators, regardless of the cylinder or the upper and lower part of the conical section, the concentration distribution in the RR-cyclone is lower than those in the C-cyclone and in the PR-cyclone. In the cylinder, the highly concentrated distribution area of PR-cyclone is wider, and this trend extends to the gas outlet, which indicates that many particles are present and cannot be separated in the center area of the cylinder for PR-cyclone. Moreover, the particles can escape from the gas outlet. In the lower part of the conical section, the concentration distribution in the RR-cyclone is almost close to zero, and a higher concentration distribution is still observed in the C-cyclone and in the PR-cyclone, which indicates that the RR-cyclone is better than the two other cyclones in terms of the separation performance or separation effective efficiency. Therefore, based on the concentration analysis at X-Y section, the RR-cyclone is better than the C-cyclone in separation efficiency, but the C-cyclone is better than PR-cyclone.
The particle concentrations in the extending area of the gas outlet are far lower than those in the area close to the edge wall of the separator. An extremely small amount of highly concentrated small regions is distributed in the Z1 section near the bottom of the gas outlet. These regional points are mainly caused by the short circuit current, and the particles in these regions can easily escape from the gas outlet, thereby lowering the separation efficiency. The highly concentrated area of PR-cyclone is larger than that of C-cyclone, and the highly concentrated area of RR-cyclone is the smallest. Therefore, the particle arrangement at the entrance has a positive effect on the elimination of short circuit current. Starting from the Z2 section, the concentration distribution shows a more regular ring. Significant differences exist between the low-concentration region close to axial area and highly concentrated region close to the wall. In the lower part of the conical section, the RR-cyclone has only single circular concentration distribution, and the C-cyclone and the PR-cyclone still have multiple circular concentration distributions, which indicates that the particles in the RR-cyclone have been captured by the wall before they had access to the lower part of the conical section, and the particles in the C-cyclone and the PR-cyclone need further separation in the lower part of the conical section.

Effect of Particle Arrangements on Separation Efficiency

Particle arrangements at the entrance are designed to solve the insufficient separation efficiency of fine particles by using a C-cyclone. The particles with small diameters are selected for comparison of the separation efficiency. Fig. 11 shows the separation efficiency curves of the three separators under 30, 40, 50, 60, and 70 m$^3$ h$^{-1}$ of the flow when the particles with diameters of 0.3, 0.6, and 1 µm in equivalent mass are filled at the entrance, with a mean diameter of 0.63 µm. The separation efficiencies of the C-cyclone, the PR-cyclone, and the RR-cyclone first increase and then decrease with the increase in flow. However, the decline of the PR-cyclone and the RR-cyclone separation efficiencies are significantly low, and the separation efficiency of the C-cyclone sharply decrease with the increase in follow-up flow. This result indicates that the separator achieves wider operational flexibility by choosing the particle arrangements.

At lower flow rate, the rotating centrifugal force is not strong, thereby making the effective particle arrangements difficult. Moreover, the separation efficiency is lower. Furthermore, the separation efficiencies of the three separators are closer to one another. At higher flow rates, the rotating centrifugal force is strong, and the turbulent kinetic energy is sharply increased, which does not only affect the effectiveness of the particle arrangements but also influences the stability of the inner flow field of the separator. This effect will aggravate the backmix of particles and cause a decrease in separation efficiency. The three separators, namely, C-cyclone, PR-cyclone, and RR-cyclone, have the highest separation efficiencies of 94%, 91%, and 99% at 50 m$^3$ h$^{-1}$, respectively. The separation efficiency of the RR-cyclone is higher than that of the two other separators at each flow rate.
Based on simulation results of single particle, particle would be more easily separated when it was closer to the wall of inlet. In our paper, particle swarm was classified as smaller particles and larger particles.

In RR-cyclone, the smaller particles were closer to the wall of inlet after the reverse arrangement. Under the function of above simulation result of “closer to wall, easier to separate”, separation efficiency of smaller particles would be better than the C-cyclone. On the other hand, larger particles were closer to the axis of inlet. However, with big diameter and mass, larger particles have natural advantages to be separated by not only C-cyclone but also RR-cyclone. In summary, RR-cyclone covers the shortage of small particles separation and takes the advantages of large particles at the same time. Hence, the overall separation efficiency could be improved in RR-cyclone.

In contrast, for PR-cyclone, the smaller particles were moved to the axis of inlet, which would let most small particles escape. The total number of escaping particles was larger than C-cyclone (The mixture status of particles at inlet of C-cyclone would favor some small particles closing to the wall to be separated). Hence, the overall separation efficiency of PR-cyclone was lower than C-cyclone.

**CONCLUSIONS**

The positions of the particles at the entrance section have significant effect on the particle tracks in a swirling flow field. The particles are more easily separated from the particle outlet when they are closer to the outer wall or at the lower part of the entrance. Otherwise, they can more easily enter into the separation blind region when the particles are closer to the inner wall or the upper part. Thus, they are more difficult to be separated from the particle outlet, with shorter tracks; moreover, short circuit current is easily generated. When the particle is larger, the generated centrifugal force is higher. Hence, the separation is easier, and it obtains minimal effect from the position change of the entrance section, with shorter track.

Particle arrangements at the entrance section have significant effects on the cyclone separation efficiency. Regardless of the cylinder or the upper and the lower part of conical section, the concentration distribution in the RR-cyclone is always lower than those that in the C-cyclone and in the PR-cyclone. Therefore, the RR-cyclone is better than the two other separators in terms of separation efficiency or separation effective time. The RR-cyclone helps the particles in avoiding the short circuit current generation region. The highly concentrated area of particles in its flow field is significantly smaller than those in two other separators.

The separation efficiencies of the three separators first increased and then decreased with the increase of flow rate. However, the decline of the PR-cyclone and RR-cyclone separation efficiency is significantly smaller. With the increase of the flow rate, the separation efficiency of the C-cyclone is increased sharply, which indicates that the separator has wider operational flexibility because of particle arrangements. The three separators, the C-cyclone, the PR-cyclone, and the RR-cyclone, have the highest separation efficiencies of 94%, 91%, and 99% at 50 m³ h⁻¹, respectively. The separation efficiency of the RR-cyclone is higher than that of the two other separators at each flow rate.

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