Numerical study of particle deposition and scaling in dust exhaust of cyclone separator

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Abstract. The solid particles accumulation in the dust exhaust cone area of the cyclone separator can cause the wall wear. This undoubtedly prevents the flue gas turbine from long period and safe operation. So it is important to study the mechanism how the particles deposited and scale on dust exhaust cone area of the cyclone separator. Numerical simulations of gas-solid flow field have been carried out in a single tube in the third cyclone separator. The three-dimensionally coupled computational fluid dynamic (CFD) technology and the modified Discrete Phase Model (DPM) are adopted to model the gas-solid two-phase flow. The results show that with the increase of the operating temperature and processing capacity, the particle sticking possibility near the cone area will rise. The sticking rates will decrease when the particle diameter becomes bigger.

1. Introduction

The scaling of particles in the gas flue with high temperature relates to the interaction between the particles and the wall surfaces, which is determined by the gas-solid two-phase flow. Two-phase flow is a complicated study field, as the solid particles in the flow interact with the flow around ceaselessly. The transfer of heat and kinetic energy occurs in the interaction. So the particles motion styles in the gas flow differ from each other. So do the interactions between the particles and the wall surfaces. And this can lead to the scaling pattern difference. In the energy recovery system, the speed of the gas is about 2-10 m/s in the exhaust-heat boiler, and about 40-80m/s in the separators. However, it can reach 400-600 m/s in the flue gas turbine. So the apparatus can be divided into two classes, the low slip speed one and the high slip speed one according to the relative moving speed between the particles and the wall surfaces. The paper mainly investigates the scaling formation in the low slip speed equipment, which can provide the theoretical foundation for the study of the scaling mechanism. As the separators are the typical equipment of the low slip speed ones, the single tube in the third cyclone separator (fig.1) has been chosen as the investigation object.
Many researchers have done lots of work in the scaling formation or flow field investigation inside the cyclone separators. Jin Ju-hui and Zhang Yang etc. [1] analyzed the operation and low separation efficiency of Fluid Catalytic Cracking (FCC) regenerator’s 3rd-stage cyclone, and found that the culprits of low separation efficiency was the higher amount of catalyst fines in flue gas and greater particle sizes, lower flue gas velocity in cyclone separator and back mixing of catalyst fines at cone section of the cyclone separator. Cao Qing-yun [2] found that particle motion was very complex and had a great randomness. For the fine particles, the main factors influencing the efficiency were the air entrainment in the inner vortex region, short-circuit flow near the vortex head and re-entrainment at the bottom of discharge cone. For the larger particles, the main influencing factors were “upper dust ring” near the top plate and short-circuit flow near the vortex head. Hou [3] analyzed the movement of particles in cyclone separators and found that the particle collision and agglomeration mainly existed in the annular space of cyclone. Particle agglomeration due to inertial collision and particle interception was dominant in the cyclone. Wu etc. [4-5] indicated that the precession vortex core (PVC) phenomenon existed in all axial positions of the cyclone separator. And the existence of the PVC would certainly induce the re-entrainment of dust and lower efficiency of the cyclone separators. Tan Hui-min etc. [6] simulated the back mixing of particles in a guide vane separator based on the Reynolds stress model (RSM) and the discrete particle model (DPM). The results showed that the back mixing of particles is serious at the bottom of the dust discharge. And many other researchers [7-11] studied the cyclone separators and gave their explanation for the performance degradation.

2. Physical Model
The geometry data is shown in fig.1. The simulation was carried out with the help of the commercial computational fluid dynamics software Fluent. Based on the finite volume method, the discrete equation was built up. The governing equation was solved with QUICK as its finite difference scheme and Semi-Implicit Method for Pressure Linked Equations (SIMPLE) as the solution method. The Reynolds stress model (RSM) was adopted to simulate the unsteady incompressible turbulent flow in the guide vane cyclone. The Reynolds stress transport equation is as follows,

$$\frac{\partial}{\partial t}(\rho u_i u_j) + \frac{\partial}{\partial x_k}(\rho U_k u_i u_j) = D_{ij} + P_{ij} + \Pi_{ij} - \epsilon_{ij}$$

(1)
In the formula, the two items in the left side is the local times derivative and the convection. The four in the right side are the stress diffusion, the stress production, the pressure strain and the dissipation from left to the right.

As the inlet particle concentration of the third cyclone separator $C_i$ is about 0.5~2.0 g/m$^3$, and the particle density is 2700 kg/m$^3$. The volume fraction of the particle $\varepsilon=C_i/\rho_p=1.85 \times 10^{-7} - 7.4 \times 10^{-7} << 1\%$. So it can be dealt as the dilute phase, and the Discrete Phase Model (DPM) can be used to simulate the particles motion.

The particles’ density in the simulation in this paper is 2700 kg/m$^3$, and their mean diameter is 18 μm. The minimum diameter of the particles is 1 μm, and the maximum diameter is 37 μm. The particles are injected to the separator with the same velocity of the gas phase at the inlet.

Boundary conditions at the entrance: the gas enters the equipment is the air at normal atmospheric temperature, and the volume flow rate $Q_i=2200$ m$^3$/h; the mass flow rate of the particles $\dot{M}_p=4.4$ kg/h. Boundary conditions at the exit: the gas flow at the exit is regarded as fully developed pipe flow. The gradient of all the parameters along the outlet normal direction is zero, viz. $\frac{\partial \rho}{\partial z}=0$. To guarantee the fully developed flow at the exit, the outlet pipe was lengthened in the computational model.

Boundary conditions near the wall: the non-slipping shear condition as well as the enhanced wall treatment was adopted. The cyclone separator wall coefficient of elastic recovery (COR) was well set by UDF.

3. Results and Discussions

3.1. Validation

By comparing the simulation results of the cyclone separator and the results obtained by the five holes probe as shown in fig.2, it can be found that the two results fit close to each other. And this indicates that the simulation results are accurate.

![Image of gas flow verification](image-url)
3.2. Particle Deposition and Scaling

In fig.3 and the figures below, the particle sticking rates $Ra$ is defined as the mass of particles sticking onto the wall surfaces in a unit interval. The deposition and scaling distribution pattern of the low slip speed equipment is illustrated in fig.6. From the picture, it is obvious that, there is a certain degree deposition on the separator wall surface. And the deposition reached the highest in the dust-exhaust cone zone. This is mainly because of a portrait swirl at the separator’s reducing area, which may make the particles wandering for a longer time here. The dust-exhaust cone in the third cyclone separator is the heaviest deterioration area. So the following study is mainly focused on this area.

![Figure 3. Distribution of particles deposition and adhesion in low sliding speed equipment.](image)

3.3. The effect of the operating parameters on the scaling inside the low slip speed equipment

3.3.1. Processing capacity

(1) Particle concentration near the wall

With the change of the processing capacity, the concentration of particles inside the equipment changes accordingly as summarized in fig.4.

![Figure 4. Distribution rules of particle concentration with different inlet flow rates.](image)
As illustrated in the picture, the gas inlet speed rises with the increase of the processing capacity. This lead to the increase of the gas flow tangential velocity and the centrifugal force exerted on the particles goes up as well. As a result, the particle concentration near the wall surface is high. However, the particle concentration is low and not sensitive to the change of the processing capacity in the central area.

(2) Particle sticking rates
As the processing capacity changes, the particle adherence insider the equipment changes accordingly as shown in fig. 5.

In fig. 5, with the increase of the processing capacity, the particle sticking rates increases in the dust-exhaust cone. This is mainly because the particle concentration nearby the wall surfaces rises, and the gas shearing velocity adjacent to the wall goes up as well. As the wall surface is arc shaped, there will be a certain degree of centrifugal force exerted to the particles on the wall. The acting force between the particles is enhanced. And this goes against the purpose of elimination of the particles on the wall surfaces and will aggravate the particles adherence to the wall surfaces.

3.3.2. Temperature
(1) Distribution of particle concentration nearby the wall
With the variation of the operating temperature, the particle concentration inside the equipment changes as well as illustrated in fig. 6. In the figure, the particle concentration adjacent to the wall surfaces goes down slightly with the increase of the operating temperature. Through changing the gas density and viscosity, the operating temperature changes the gas flow field and makes the interaction between the gas and particles change. Then the particle trajectories change and the drag force exerted on the particles increases when the operating temperature goes up. And this affects the particle concentration distribution.

(2) Particle sticking rates
In fig. 7, the sticking rates get high in the dust exhaust area and goes down in the cylinder shell area with the increase of the operating temperature. The interaction between the temperature and the Young’s modulus is adopted in this paper. As the Young’s modulus reflects the particles’ capacity to resist the deformation, the decrease of Young’s modulus with the increase of temperature means it is easier for the particles to get stuck by the wall surfaces with the increase of operating temperature. With the variation of the operating temperature, the particle sticking rates changes as well.
3.3.3. **Input concentration.** In fig.8, with the increase of the input concentration, the particle concentration nearby the equipment inside wall surfaces is certain to rise. With the sum of particles goes up, the possibility of collision between the particles and the wall surfaces becomes bigger, and the sticking rates in the dust-exhaust cone area is apparently higher.

3.3.4. **Particle diameter.** Apparently as illustrated in fig.9, with the variation of the particle diameter, the particle sticking rates change.

The maximum sticking rates on the wall surfaces decrease when the particle diameter rises. This indicates that the smaller the particle diameter, the bigger chance the scaling will occur. Particles at 1μm are apt to move with the gas flow, so their separation efficiency is the lowest. And they are less possibly to approach the dust-exhaust cone area, and get captured by the wall surfaces. The larger the particles diameters, the bigger chance they will be captured until the diameter reaches 5μm. After that, the sticking area as well as the sticking rates goes down with the increase of the particle diameter in the dust-exhaust area. When the diameter reaches 10μm, there will be no more particles sticking on the
dust-exhaust area. This indicates that it is mainly particles with diameters below 10μm that affect the scaling in the dust-exhaust area, and the sticking rates decreases with the increase of the particle diameter.

\textbf{Figure 8.} Variation of particle sticking rates with different particle concentrations.

\textbf{Figure 9.} Distribution of particle sticking rates with different particle sizes.

4. Conclusions
This paper studies the gas-solid two phase flow inside the low slip speed velocity equipment. The gas shearing velocity and the particle concentration distribution as well as the particle sticking rates near the wall surfaces are analyzed. The study also covers the effects of the operating parameters and physical parameters as well as the structural parameters on the particle sticking rates. The six conclusions are drawn out as follows:
(1) Scaling in the dust exhaust cone area is the severest in the low slip speed equipment.
(2) The high particles concentration makes the possibility of scaling on the dust exhaust cone area get bigger. The particle concentration nearing the wall are not sensitive to the operating temperature. But with the increase of the operating temperature, the particle sticking possibility near the cone area will rise.
(3) When the particle concentration gets higher, the possibility of collision between the particles and the wall surfaces gets bigger. The sticking rates in the cone area go up apparently. The sticking rates will decrease as when the particle diameter is bigger. And the diameters of the particles caused the scaling are mainly under 10μm.

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