Numerical Simulation of Particle Separation in PM$_{10}$ Cyclone Separator

Jing-lu DAI$^{1,2}$, Yi-ping LU$^{1,*}$, Song-song ZHANG$^2$, Guo-li QI$^2$ and Ya-qing LI$^3$

$^1$No. 52, Xuefu Road, Nangang District, Harbin City, Harbin University of Science and Technology, Heilongjiang Province, P.R. China, 150080

$^2$Building 2, Hepingjie, Xiyuan, Chaoyang District, Beijing, P.R. China. 100029

$^3$The Compound of Huanbao, The Road of Xinping Wang Wei, Datong Mining Area of Shanxi

*Corresponding author

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Abstract. Electrical Low Pressure Impactor is a measurement device, which can real-time measure the distribution of particle size and concentration. The PM$_{10}$ cyclone separator is used as the pretreatment device of the Electrical Low Pressure Impactor, so the separation performance of the cyclone separator is the key factor to measure the particle concentration accurately. ICEM was adopted to mesh, and gas-solid two-phase flow of the separator was studied based on Reynolds stress model and the stochastic model. The result shows that the internal flow field in the pre-separator is the force vortex state, the outer swirl is the composite vortex structure of quasi free vortex, the composite vortex has a good effect on particle separation. The change of dust discharge diameter adjusts the critical diameter to the theoretical value, which making more particles whose size larger than 10µm were collected to the maximum extent, which provides a guarantee for the accurate measurement of particle concentration.

Introduction

According to their aerodynamic diameter sizes, the suspended particles in the air can be divided into the TSP, PM$_{10}$, PM$_{2.5}$. Ambient air particulates with different diameters have a great deal of harm to the environment and human health [1,2], therefore there is a need for real-time monitoring and forecasting of PM$_{10}$ and PM$_{2.5}$ [3]. Based on the analysis, using a combination of PM$_{10}$ cyclone separator, diluted device and Electrical Low Pressure Impactor(ELPI), can real-time accurately measure the particle concentration of different sizes accurately. PM$_{10}$ cyclone separator is used to separate particles with particle size greater than 10µm, and the gas including particles with particle size less than 10µm was used by ELPI for real-time measurement after diluting and cooling[4]. Di Wenjing carried out the numerical simulation of cyclone separator and analyzed the effects of inlet velocity and geometrical parameters on the separation performance. However, the accuracy of the critical particle size of the pre-separator does not have many researches. As a pretreatment device for particle concentration measurement, the separation performance is directly related to the accuracy of the measurement of the particle concentration[5,6,7].

The study on characteristic of gas-solid two-phase flow in PM$_{10}$ cyclone separator is used by Reynolds stress model and stochastic trajectory model of coupling between phases. Analyzing the distribution of gas phase tangential velocity and particle separation efficiency of different dust discharge diameter, which provides guidance for the size optimization of the separator.

Physical Model

The cylinder diameter of PM$_{10}$-cyclone separator is 45 mm in this paper, and the geometric structure is shown in Figure 1, the grid is shown in Figure 2. Specific geometry is shown in Table 1. This separator is divided into four parts: entrance, cylindrical segment and vertebral segment, exporting segment.
Mathematical Model and Parameters Setting

Control Equation of Gas-phase Motion

Gas phase governing equations include the continuity equation, the momentum equation, and turbulence model. Reynolds stress model (RSM) is introduced, it completely abandons the Boussinesq hypothesis based on isotropic Eddy viscosity, and the effect of anisotropy of turbulence is taken into account totally, especially rotation effects, buoyancy effects and effects of curvature, have potential for high accuracy prediction for complex flows [9].

Control Equation of Particle Motion

Based on the simulation of gas-phase flow field, a single particle phase is processed in the Euler-Lagrangian coordinate system, and a large number of particle trajectories are analyzed statistically to obtain the motion profile of the particles. Assuming the particle is a sphere, the density is 2600 kg/m³. The main force of the particles in the cutter is centrifugal force and resistance, and other forces are small, which can be ignored. In the Lagrangian coordinates, the motion equation of individual particles can be shown as [10]:

\[ m \frac{du_p}{dt} = F_d + mg \]  

(1)

where \( F_d \) is the drag force of the particle, it is calculated using the following equation:

\[ F_d = \frac{\beta}{\varepsilon_p} \left(u_f - v_p\right) \]  

(2)

Where \( \varepsilon_p \) is the volume fraction of particles in the computational grid, \( \beta \) is drag coefficient, which is calculated using Koch &Hill correlation as follows:

\[ \beta = \frac{18 \mu \varepsilon_p^2}{d^2 p} \left( F_0(\varepsilon_p) + \frac{1}{2} F_3(\varepsilon_p) \right) \]  

(3)

where \( F_0(\varepsilon_p) \) and \( F_3(\varepsilon_p) \) are intermediate functions, \( Re_p \) is Reynolds number of particles.

Setting Parameters

The separation of particles in the fluid is simulated, and associated setting parameters are shown in Table 2 below.
Table 2. Setting parameters.

<table>
<thead>
<tr>
<th>Particle property</th>
<th>Fluid characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density [kg/m³] : 2600</td>
<td>Fluid type : atmosphere</td>
</tr>
<tr>
<td>Volume flow [m³/s] : 1×10⁻⁵</td>
<td>Density [kg/m³] : 1.29</td>
</tr>
<tr>
<td>Particle size distribution: Rosin-Rammler distribution [8]</td>
<td>Viscosity [kg/(m × s)] : 1.81 × 10⁻⁵</td>
</tr>
</tbody>
</table>

**Result and Analysis**

The gas solid two-phase flow in PM₁₀ cyclone separator is the separation process of gas phase and particles phase. Assuming particles phase belongs to sparse phase, The motion of particles is largely determined by the gas flow field in the separator. Therefore, it is significative to analysis the characteristics of the gas flow field in the cyclone separator for the study of the particle trajectory and the separation performance of the PM₁₀ cyclone separator[11].

**Tangential Velocity Distribution of Gas-Phase**

A three dimensional rotating turbulent motion occurs in PM₁₀ cyclone separator, and the flow is particularly complex, the velocity of any point can be divided into tangential speed, axial and radial velocity, tangential velocity is in the dominant position, the stronger the centrifugal field force, the higher the separation efficiency. As the speed increases, the pressure loss will increase and the high air velocity will aggravate the particle crushing and the wear of the separator wall, so it is necessary to study the tangential velocity. The contour map of tangential velocity in the z=0 section of PM₁₀ cyclone separator is shown on Figure 3.

![Figure 3. Tangential velocity profile.](image)

Different from the ordinary cyclone separator, the PM₁₀ cyclone separator is the pretreatment device before the ELPI. Because of the limit of the critical particle size, the inlet diameter is relatively large[12]. However, the symmetry of tangential velocity at the lower part of the exhaust pipe is still relatively good, which reflects the characteristics of the strong swirl in the separator. This form of flow is good for particle separation. The tangential velocity of air flow is larger at the lower edge of the exhaust pipe and turbulent flow is violent. As the inlet diameter is relatively large, it is close to the lower edge of the exhaust port, resulting in some of the fluid flow enters the exhaust pipe directly from the inlet to form a short circuit flow. It makes some particles which are not separated directly into the particle concentration monitoring instrument, not only lead to the false results of particle concentration, but also possibly cause damage to the instrument. Due to the mixed collision caused by high speed external and internal swirling flow in the bottom of the cone, it produced some irregular local secondary Vortex, resulting some particles that have been collected in the bottom to be involved in internal swirl. Finally, it is discharged from the exhaust pipe, which reduces the separation efficiency and interferes with the subsequent measurement results.

The tangential velocity of different height section is shown on Figure 4. The flow field in the separator has the characteristics of combined vortex, the points of maximum tangential velocity at
different heights form an interface, which is similar to cylindrical surface. At this interface, the flow field is divided into an outer quasi free vortex and an inner quasi forced vortex. Through centrifugal effect of the Vortex motion in separator, particles whose particle size greater than 10µm are thrown outward. The effect on particles is weakening as the low intensity of the quasi free vortex flow, especially near wall turbulence close to zero, so large particles near the wall can be easily captured, this internal and external flow is very favorable for separation.

Figure 4. Tangential velocity distribution at different heights.

Analysis of Particle Separation Efficiency

The particle diameter of atmospheric particles which are separated by PM10 cyclone separator less than or equal to 10µm. The critical particle size is 10µm after theoretical calculation, and 10µm is a statistical value, namely particles whose size equal to 10µm have 50% possibilities to pass through the separator. The numerical calculation results of the particle separation efficiency for the separator is shown on Table 3 when the entrance flow rate is 10L/min. It can be seen that the actual critical particle size is different from the theoretical calculation result. In theory, for the cyclone separator with the critical particle size, the particles smaller than the critical particle are all discharged from the dust discharge hole, and the particles larger than the critical particle are all captured. In practice, the effect of collisions between particles, static electricity and the short circuit effect lead particle motion to have great randomness, part of small particles may be trapped, part of larger particles may be composed of dust port. Described in the above two points, under the conditions of this article without changing other dimensions, increasing the diameter of the dust discharge port adjusts the actual critical particle size, which provide a guarantee for subsequent measurement.

Table 3. Particle separation efficiency.

<table>
<thead>
<tr>
<th>Particle size(µm)</th>
<th>1.00</th>
<th>2.56</th>
<th>4.11</th>
<th>5.67</th>
<th>7.22</th>
<th>8.78</th>
<th>9.24</th>
<th>10.30</th>
<th>11.90</th>
<th>13.40</th>
</tr>
</thead>
<tbody>
<tr>
<td>Separation efficiency(%)</td>
<td>0.94</td>
<td>0.93</td>
<td>0.91</td>
<td>0.85</td>
<td>0.77</td>
<td>0.59</td>
<td>0.50</td>
<td>0.28</td>
<td>0.16</td>
<td>0.11</td>
</tr>
</tbody>
</table>

In this paper, The dust discharge diameter of the original model is set to 20mm, the diameter of the second scheme is set to 19mm, the diameter of the third scheme is set to 18mm, respectively, the numerical simulation of gas-solid two-phase in the three schemes, the separation efficiency of each particle size is drawn as curves which shown in Fig. 5. After analyzing the separation efficiency of the particle sizes of three schemes in Fig. 5, in the 3rd scheme, the actual critical particle size of the separator is 9.96µm, compared to the other two schemes, the actual critical separation particle diameter of this scheme is closer to the theoretical critical particle diameter, and for the particles with larger diameter, the trapping rate increases in varying degrees. The main reason is shown in Figure 6-Figure 8, by the tangential velocity distribution of three different height of the cross-section, the maximum tangential velocity point in the three different height section of the 3rd scheme is moving towards the inside radial direction. The external swirl zone increase, that is, the decreasing area of the particle carrying effect relative increase, making the trapping efficiency of the separator increase. The maximum tangential velocity of each section of the 3rd scheme increases in varying degrees, thus the centrifugal field force increases, and more particles
are separated from the wall of the separator under centrifugal effect, so that the actual critical particle size decreases, and the separation efficiency of the separator is more accurate.

Figure 5. Effect of exhaust pipe diameter on separation efficiency.

Figure 6. Tangential velocity distribution of each scheme on 40mm height section.

Figure 7. Tangential velocity distribution of each scheme on 35mm height section.

Figure 8. Tangential velocity distribution of each scheme on 30mm height section.

Summary

1. The velocity distributions of cylindrical segments of the separator are less symmetrical, the speed of air inlet side is obviously greater than the other side, the velocity distribution of conical segment are better symmetrical, the strong rotating flow in the separator decreases the asymmetry of velocity distribution caused by the single-side inlet, which has good effect on the separation of particles.

2. The tangential velocity near the wall is lower, especially the turbulent intensity near the wall is 0, the external quasi-free vortex swirl intensity is lower than the particles carrying effect, the large diameter particles are more easily arrested near the wall.

3. Adjusting the diameter of the exhaust outlet reasonably change the maximum tangential velocity and the relative size of the external quasi-force vortex and the internal quasi-forced Eddy region of the flow field, finally, the critical particle diameter is changed from 11.2 µm to 9.96 µm, the separation efficiency of the separator is more accurate.

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References


