Analysis of the Combined Cyclone and Filter Cartridge Separator for a Hazardous Materials Rescue Truck

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Abstract: In accidents during the transportation of hazardous materials, it is necessary to filter the collected substances when a hazardous materials rescue truck is used to collect the hazardous materials; this method is sometimes called gas-solid separation. There are many devices used for gas-solid separation. In this paper, the most commonly used separation devices, namely, the cyclone separator and the filter cartridge, are combined to form a new filtration device. The advantages of each of these devices are utilized to achieve effective separation of solid particles and prevent secondary pollution. First, the model of this new type of separator is built. Next, the model is divided into grids, with an effort to ensure the grid quality is the best. The model is imported into FLUENT software after dividing the hexahedral structured grid. The Reynolds stress model (RSM) is selected to simulate the continuous phase, and the discrete phase model is used to simulate the particle. Finally, the trajectory of the particles is examined and the simulation results are analyzed.

1 INTRODUCTION

In the handling of hazardous materials from leakage accidents, the rescue truck first collects the hazardous materials and then uses the filter separation device to separate the gas and solids to prevent secondary pollution. A hazardous materials storage truck is shown in Figure 1.

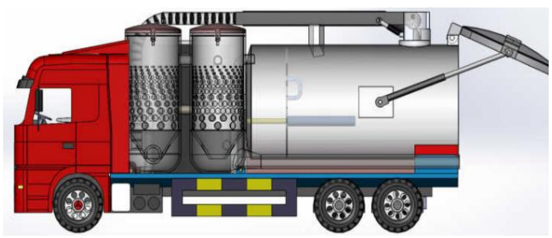

Figure 1: Hazardous materials rescue truck.

1.1 Methods of Gas-solid Separation

There are four main types of common gas-solid separation methods: mechanical force separation, electrostatic separation, filtration separation and wet separation(Cen et al., 1999).

The mechanical separation is represented by the cyclone separator (centrifugal separation). It can be used under various harsh conditions, such as high temperature, high pressure and strong corrosion. Another method is filtration separation, this method is represented by a filter cartridge type dust collector, which can effectively capture particles from 0.1 μm to 5 μm. Wet dust collectors are not suitable for the separation and filtration of hazardous Materials and chemical corrosion. Thus cyclone separator and filter cartridge type dust collector suitable for hazardous materials storage truck.

1.2 Shortcomings of Cyclone Separator and Filter Cartridge Separator

The cyclone separator can be used under various harsh conditions, but it is very inefficient in separating tiny particles (below 5 μm) because of the short-circuit flow and the upper ash ring (Hoffmann et al., 2002).

Filter cartridge type dust collector can effectively capture particles from 0.1 μm to 5 μm(Gu et al., 2002). But most of the particles will be removed on the surface of the filter cartridge. This will increase the blockage and breakage of the filter cartridge,

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resulting in high frequency replacement. Therefore, the filter cartridge dust collector maintenance fee will be higher.

2 MODEL OF THE COMPOSITE SEPARATOR

In this paper, the external structure of the cyclone is kept and the filter cartridge is added in the exhaust pipe of the cyclone separator. This approach keeps the original working characteristics of the cyclone separator, which can handle 5 µm to 10 µm hazardous particles. The filter cartridge added to the exhaust pipe of the cyclone can capture the tiny particles that cannot be separated because of the short-circuit flow and the upper ash ring. This method addresses the shortcomings of the cyclone separator. Only a small portion of the tiny particles are captured by the filter cartridge. Most of the particles are captured by the centrifugal force of the cyclone separator(Ge et al., 2006). This will increase the service life of the filter cartridge.

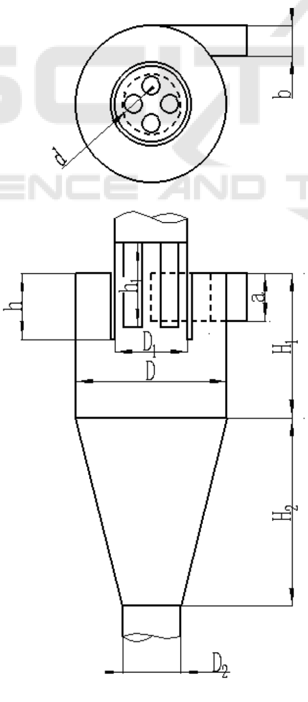

Figure 2: Diagram of the structure of the separator.

The simplify structure of the composite cyclone and filter cartridge separator is shown in Figure 2. The proposed separator consists of an air-inlet, a cylinder, a cone, a dust-outlet, an exhaust-vent and filter cartridges. The parameters of the model are shown in the Table 1. The filter cartridge, which is based on the filter bag, consists of a top cover, a metal frame, a corrugated frame, a seal ring and a base. It is repeatedly folded from the filter material and then combined into a barrel shape. Thus, the filter cartridge solves the problem of the small filter area of the filter bag (Zhang, 2015).

Table 1: The model parameters.

air-inlet length(a)	a=160mm
exhaust-vent diameter(D_1)	D_1=250mm
dust-outlet diameter(D_2)	D_2=200mm
Cylinder height(H_1)	H_1=480mm
Cone height(H_2)	H_2=640mm

3 THE ESTABLISHMENT OF THE FINITE ELEMENT MODEL

3.1 Selection of Meshing Methods

Meshing can be roughly divided into two types: structured meshing and unstructured meshing(Zhou, 2001). The internal flow field of the cyclone and filter cartridge composite separator is complicated. In order to achieve accurate calculations for it, the entire structure needs structured (hexahedral) meshing(Hu et al., 2014). Structured grids have the following advantages.

(1) The calculation accuracy of the hexahedral mesh is relatively high.

(2) Most of the fits of surfaces or spaces are obtained by parametric or spline interpolation with smooth regions that are close to the actual model.

(3) The boundary fitting of regions is easily achieved, making structured grids suitable for fluid calculations.

3.2 Meshing Analysis of the Proposed Model

Because the structure of the cyclone filter separator is complicated, it will be simplified during meshing. This simplification will not only reduce the difficulty of meshing (thereby increasing the quality of the hexahedral mesh) but also reduce the complexity of flow field analysis when importing FLUENT analysis. In this article, the following processing was performed on the model.

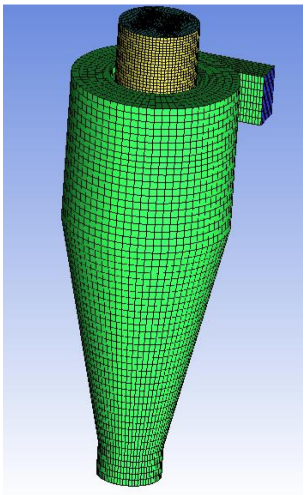

Figure 3: The hexahedral structured grid.

(1) The filter cartridge has much geometric porosity, making meshing difficult to achieve. Thus, the geometrical pores are simplified during geometric meshing, and the filter cartridge is considered a cylinder. The cylindrical region is set to a porous medium fluid domain with a resistance source during fluid analysis(Hu et al., 2017). Generally, a velocity-dependent momentum is provided in the porous region; the expression of this momentum is as follows:

$$S_i = -(\frac{\mu}{\alpha}\upsilon_i + C_2\frac{1}{2}|v|v_i) \qquad (1)$$

In the expression, α is the permeability; C2 is the inertia drag coefficient. The first term on the right side is the viscous loss term, and the second term is the inertia loss term.

(2) When establishing the combination model, the influence of the partial cleaning device above the filter cartridge is not considered and is omitted during meshing. The final structured hexahedral mesh of the model is shown in Figure 3.

4 SIMULATION OF THE MODEL IN FLUENT

4.1 The Model Calculation Method

Because hazardous materials rescue trucks use vacuum negative pressure to collect hazardous materials particles and the collection is two-phase flow with a particle volume fraction less than ten percent, in the FLUENT simulation analysis, the continuous phase flow of the gas is simulated and then the Lagrangian trajectory method is used to track the particle trajectory(Hoffmann et al., 2002).

The flow in the cyclone and filter separator is a complex two-phase flow with three-dimensional strong rotational turbulence. According to the strong rotating turbulent flow field of the cyclone and the porous medium model of the filter cartridge, the following can be concluded:

(1) The turbulence model selected is the Reynolds stress model(RSM). It is suitable for high rotational flow. The Reynolds stress model takes into account the rapid changes in streamline bending, vortex, rotation and tension. The Reynolds stress model has a higher accuracy prediction potential for complex flows. The transport equations(Zhou, 2001) for the components of the Reynolds stress are as follows:

$$\frac{\partial\left(\rho\overline{\mu_i^{'}u_j^{'}}\right)}{\partial t} + \frac{\partial\left(\rho u_k\overline{u_i^{'}u_j^{'}}\right)}{\partial x_k} = D_{i,j} + P_{i,j} + G_{i,j} + M_{i,j} - B_{i,j} + F_{i,j} + S_{user} \qquad (2)$$

In the expression, Di,j is diffusion term, Pi,j is stress generation term, Gi,j is buoyancy generation term, Mi,j is pressure strain redistribution term, Bi,j is discrete term, Fi,j is rotation system generation term.

(2) For pressure and speed coupling, the SIMPLE format is selected. Because PISO better computes the non-steady state situation(Song,2011) and COUPLED does not apply to porous media, according to the complexity of the combined model, the SIMPLE format is chosen for calculation.

(3) Pressure interpolation is based on the PRESTO format. Because PRESTO is well suited for high-speed rotary flow and porous media models, it can better reflect the combined internal flow field flow.

4.2 Simulation Results

The grid divided in the ICEM software is imported into the FLUENT software for performing the simulations used to analyze the problems involving the new cyclone filter separator. The simulation results are shown in Figure 4 to Figure 6.

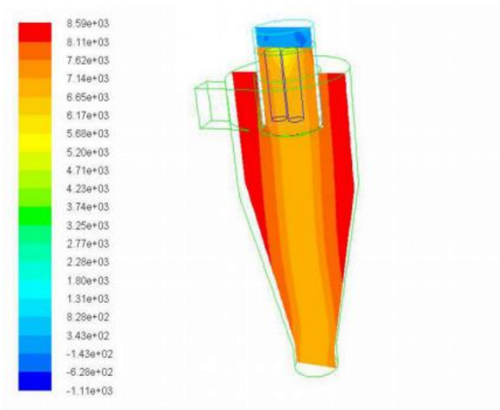

Figure 4: The pressure contour of the internal flow field.

Figure 4 shows the internal static pressure contour. The figure reveals that the internal pressure of the separator is symmetrically distributed and the pressure on the wall is high. The pressure shows a decreasing trend moving away from the wall, with the pressure at the center being small. Simulation of a single inlet separator in this article results in a slight oscillation of the pressure above the dust-outlet. The maximum pressure inside the combined model is 6.6 times the same size cyclone separator, and the pressure gradient is 6.8 times the original.

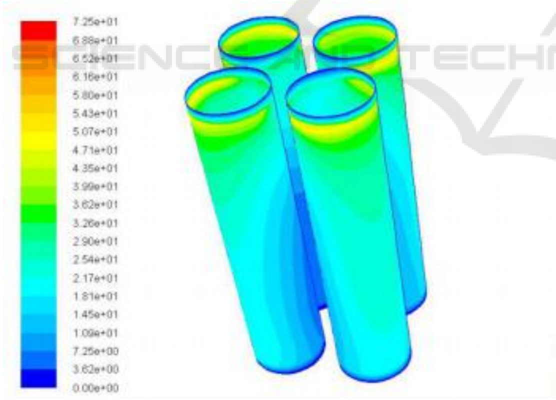

Figure 5: The speed contour of the cartridge surface.

Figure 5 shows the velocity contour of the filter cartridge surface. It can be seen that the speed on the surface of the filter cartridge is relatively high, whereas the speed near the center of the four filter cartridges is low. Because the air stream at the exhaust-pipe is rotating upward, most of the tiny particles that are not collected by the dust-outlet are rotated around the airflow and then collected by the outside surface of the filter cartridge. This process will cause the filter cartridge on the outer and upper part to be washed heavily. Here, the appropriate baffle is selected to reduce this phenomenon.

To analyze the separation efficiency of particles of different sizes, 9~0.1 μm diameter particles are selected to be uniformly injected from the inlet. Figure 6 (a) shows the 9 μm particle trajectory tracking results, and Figure 6 (b) shows the 0.1 μm particle trajectory tracking results. The capture rate of 9~0.1 μm particles reaches 100%. Most of the large-diameter particles are found to be thrown into the wall after entering the cyclone separator before finally falling into the dust exhaust port. These particles can be directly separated by the structure of the cyclone separator. In contrast, only a small fraction of the particles are directly brought from below the exhaust pipe to the filter cartridge or are brought to the filter cartridge along with the inner vortex and then captured by the filter cartridge.

(a) (b)

Figure 6: The trajectory tracking of particles.

5 CONCLUSIONS

The combination of the cyclone and the filter cartridge in this article retains most of the external structure of the cyclone, with only four filter cartridges added to the exhaust pipe. The simulation results reveal that the proposed separator not only utilizes the characteristics of the original cyclone separator (which can better separate 5~10 μm particles) but also utilizes the characteristics of the filter cartridge (which can better capture the tiny particles). An excessive number of filter cartridges are not added because most of the particles have been separated by the cyclone prior to the filter cartridges, and only a small fraction of the particles will move to the exhaust pipe. Thus, the working demand of the filter cartridge is not very high. This proposed combined separator model can better capture hazardous particles compared to the individual separators alone.

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