Simulation analysis of gas-solid separation system for hazardous materials’ collection truck

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Abstract. In view of the hazardous materials’ leakage caused by traffic accidents during their transportation, a concept and design of a hazardous materials’ collection truck is proposed for a safe collection and transportation to a professional processing factory. In order to prevent secondary pollution caused by hazardous materials in the vacuum collection process, the gas-solid separation operation must be performed in the hazardous materials collection truck. According to the needs of the gas-solid separation, the structural composition and working principle of the hazardous materials collection truck were analyzed, and the separator was modeled by the finite element analysis method. In the simulation process, the continuous phase flow field simulation of the air is performed first, and on this basis, the discrete phase analysis of the particles is added. The effects of gas flow inlet velocity and particle size on the separation efficiency of the separator were analyzed. Based on the response surface method, the structure of cyclone separator was improved to find the optimal solution and enhance the separation efficiency.

1. Introduction
In the process of transportation of hazardous materials, in the event of a traffic accident, solid hazardous materials (such as chemical powder raw materials, highly toxic solid particulate matter, etc.) are likely to be scattered on the ground. In the process of collecting with a dedicated collection truck, multi-media separation and filtration must be carried out on the collected materials, that is, gas-solid separation, to avoid secondary pollution. The schematic diagram of the hazardous materials leakage collection truck is shown in figure 1.

The common methods for separation include: separation of homogeneous materials, i.e. mass transfer separation, separation process based on diffusion of matter, such as steaming, absorption, extraction, drying, etc. The separation of heterogeneous materials, that is, mechanical separation, is a separation process that does not rely on diffusion, such as sedimentation, filtration, and the like. Among the heterogeneous substances, they are classified into two types: gas-solid heterogeneous and liquid-solid heterogeneous. When the gas is a continuous phase, the solid particles are dispersed in the gas, at which time the solid is a dispersed phase, which is a gas-solid heterogeneous material. For gas-solid phase separation, gravity settlement and centrifugal sedimentation are mostly used to solve. Electrostatic dust removal and wet scrubbing of gases can also separate gas-solids [1, 2].

Since the separation factor of centrifugal separation is much larger than gravity separation, that is, the separation speed of the former is much larger than that of the latter.
The cyclone will be used as the primary separator for the separation of the collected gas-solid hazardous materials. The fine particles escaped from the cyclone will be intercepted by the filter cartridge. This paper will mainly discuss the design of the cyclone separator for dangerous goods leakage storage vehicles, and carry out fluid dynamics simulation analysis.

![Hazardous materials collection truck](image)

**Figure 1. Hazardous materials collection truck**

2. **Separator working principle**

The structure of the cyclone separator is shown in figure 2. It is mainly composed of an upper cylinder and a lower cone. The gas containing the hazardous materials particles enters from the intake pipe of the cylinder in the tangential direction, descends along the spiral path, spirals up at the center position near the bottom, and is discharged from the central air pipe. During the rotation process, the particulate matter entrained by the airflow falls toward the wall of the cylinder at a high speed due to the centrifugal force, and falls into the hopper from the bottom of the cone. Small particles are carried away by high-speed airflow before reaching the wall, which leads to a drop in separation efficiency [3, 4].
The smallest particle diameter that the separator can completely separate is called the critical particle size. The empirical formula for calculating the critical particle size given below [1]:

\[ d_c \geq \left( \frac{9B\mu}{\pi N_e \rho_s u_i} \right)^{1/2} \]  

(1)

where \( d_c \) is critical particle diameter, \( B \) is separator inlet width, \( \rho_s \) is Particle density, \( u_i \) is inlet airflow speed, \( N_e \) is effective number of revolutions of airflow.

The critical particle diameter theory is derived based on a simplified model. It is believed that particles larger than the critical particle diameter can be removed, and particles smaller than the critical particle diameter can only be partially removed, which is a little different from the results of experiments and simulations [2].

The separation efficiency refers to the ratio of removed hazardous materials and their original amount [2]:

\[ \eta_s = \frac{c_i - c_o}{c_i} \]  

(2)

where \( \eta_s \) is separation efficiency, \( c_i \) and \( c_o \) are concentrations of particles contained in the inlet and outlet gas, respectively.

3. The finite element model

The cyclone separator is a device that performs gas-solid separation using the principle of centrifugal sedimentation. The whole is a static structure with no moving parts, including volute, intake pipe, exhaust pipe, cylinder and cone.

In the process of modelling, it is necessary to avoid the "top-to-bottom" moding method of constructing the entire geometry, then dividing the geometry into blocks, and finally generating a structured grid of multiple blocks. Because this geometric segmentation is prone to errors of duplicate points, repeated lines, or repeated surface [5].

Figure 2. The diagram of cyclone structure
Therefore, before establishing the separator geometry, according to the structural characteristics and topological relations of each part, a reasonable block mode is selected, from point to line, then line to face, and finally from face to volume. Figure 3 shows a model of a cyclone separator, in which (a) is a solid model and (b) is a mesh model.

![Models of a cyclone separator](image)

**Figure 3.** Models of a cyclone separator

In the boundary type setting, since the outer side wall surface of the separator has a mesh on only one side, data cannot be transmitted to the outer space of the separator through the wall surface, and the fluid cannot flow out, so the outer side wall surface of the separator does not need to define a boundary, and the default is the wall surface. However, for the exhaust pipe inserted into the volute, a mesh is arranged on both sides of the wall, so the boundary type of the wall must be defined as WALL.

When the discrete phase gas-solid two-phase flow simulation of the particulate matter is carried out, the number of particles cannot be set due to the limitations of the simulation software. The number of particles is equal to the number of cells in the cross section of the intake pipe, so to increase the number of simulated particles, one has to increase the number of cross-sectional nodes of the intake pipe beforehand.

4. Simulation results and their analysis

According to the characteristics of the working conditions, the hazardous materials collection truck collects the hazardous solid particles of the leaked hazardous by vacuum negative pressure. The particles move in a dispersed manner in the gas flow, and the interaction between the particles has no obvious influence on the movement, and belongs to a two-phase flow of a dilute phase flow. The gas in the two-phase flow is air, and the air is selected in the material model. The particles are caustic soda and have a density of 2100 kg/m³. In the simulation, the continuous phase flow field simulation analysis of the air is carried out, and on this basis, the discrete phase analysis of the particles is added.

The flow field in the separator is a complex three-dimensional strong rotating turbulent flow field with strong anisotropy. The Reynolds stress model can be used for turbulence simulation. This method requires a large amount of calculation and requires a long time for convergence. It can also be calculated first by RNG k-ε turbulence model, and then switched to the Reynolds stress model after convergence [6]. The simulation results are shown in figures 4 and 5. Figure 4 is a pressure contour of the internal flow field of the separator at the z = -0.1 section. As can be seen from the figure, the vicinity of the longitudinal axis of the separator is a low-pressure zone, while the high-pressure zone is mainly concentrated near the wall of the cylinder.
On the basis of continuous phase simulation analysis, the simulation of discrete phase particle motion is carried out. By calculating the mass flow of the particles (since the particle size and density are assumed to be the same, the correlation can be calculated according to the number of particles). According to the total number of imported particles and the number of particles captured, different inlet velocities and different particle diameters can be calculated. The separation efficiency of the lower separator is shown in Figure 5.

It can be seen from Figure 5 that in a certain interval, the separation efficiency increases as the particle diameter and inlet velocity increase.

5. Structural parameter optimization of cyclone separator

In order to optimize the separation efficiency and energy loss of the cyclone separator, the main structural parameters affecting the performance of the cyclone separator are determined using the response surface model and CFD numerical simulation. Design variables with dust vent diameter (B), exhaust port diameter (d), barrel part length (H), cone part length (He), with the total separation efficiency as the goal function, the optimization design analysis of the four factors is carried out.

The results show that the diameter of the dust vent has little effect on the separation efficiency, and the diameter of the exhaust port and the length of the cone have a significant effect on the separation efficiency. The recommended optimal parameter combinations are B/D=0.55, D/D=0.475, H/D=1.55, He/D=1.75, where D is the cylinder diameter. Compared with the experimental structure, the separation efficiency was increased from 77.8% to 85.8%, which indicates that the established response surface model can more accurately represent the relationship between the design variable and the target function, and the optimization design method based on the response surface model can be used effectively for the structural optimization of the cyclone separator. Figure 6 shows the optimization of the front and rear structure contrast, a for the optimization of the structure size before, b for the optimized structure size.
X1, X2, X3, X4 are used to represent the exhaust pipe diameter \(d/D\), the dust vent diameter \(B/D\), the cylinder height \(H/D\), the cone height \(He/D\). When the optimization parameters change continuously, there are infinite combinations of separators, for which the discrete optimization parameter variables are five equal-step horizontal variations. These are coded as \(-2, -1, 0, +1, +2\), while \(\Delta j\) is the change step. More data are given in Table 1.

**Table 1.** Table of secondary regression test factors and horizontal coding values

| Level | X1   | X2   | X3   | X4   |
|-------|------|------|------|------|
| -2    | 0.175| 0.25 | 0.65 | 0.25 |
| -1    | 0.275| 0.35 | 0.95 | 0.75 |
| 0     | 0.375| 0.45 | 1.25 | 1.25 |
| 1     | 0.475| 0.55 | 1.55 | 1.75 |
| 2     | 0.575| 0.65 | 1.85 | 2.25 |
| \(\Delta j\) | 0.1  | 0.1  | 0.3  | 0.5  |

The five for-factor horizontal data were incorporated into the Design-Expert software, and 29 structural combinations were obtained. The 29 structures are modeled, meshed, and simulated. After analyzing the relationship between the factors and the response face, the optimal solution is obtained. The best design points are exhaust pipe diameter \(d=110\)mm, dust vent diameter \(B=220\) mm, cylinder height \(H=620\)mm and cone height \(He=700\)mm, the total separation efficiency is 87.908%; Using the above structural parameters to calculate and verify the model, the actual total separation efficiency is 85.8%, which is basically in line with the theoretical prediction value, and is 8% higher than the total separation efficiency of 77.8% before optimization, it is shown that this method can truly reflect the influence of influencing factors on the separation efficiency of cyclone separators. The changes of parameters before and after model optimization are shown in table 2.
Table 2. Comparison of results before and after the optimization

|        | D (mm) | B (mm) | H (mm) | He (mm) | Separation efficiency (%) |
|--------|--------|--------|--------|---------|---------------------------|
| Before | 150    | 180    | 500    | 500     | 77.8                      |
| After  | 110    | 220    | 620    | 700     | 85.8                      |

Through the analysis of the optimization of the software, it is found that the most important factors in the separation efficiency of the cyclone separator are the diameter of the exhaust pipe and the height of the cone segment. With the decrease of the diameter of the exhaust pipe and the increase of the height of the cone segment, the separation efficiency increases significantly. The second is the height of the cylinder segment, and with the increase of the height of the cylinder segment, the separation efficiency is gradually increased. The diameter size of the dust vent has little effect on the separation efficiency.

6. Conclusion
In this paper, the structure and working principle of the separator for hazardous materials collection truck was analyzed. The finite element analysis method is used to model the separator and two-phase flow simulation analysis. The separation efficiency of the separator is affected by many factors. The influence of inlet velocity and particle diameter on the separation efficiency was analyzed. Based on the response surface method, the structure of the cyclone separator is optimized, the influence of the structural parameters on the separation efficiency is analyzed, and the separation efficiency of the separator is improved.

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