Study on dump truck dumping process and dust extraction device design

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Abstract: The particle diffusion and movement rules of the dump truck dumping material are simulated in Fluent based on the gas-solid two-phase flow theory. The simulation results show that the dust generation mainly occurs in two stages. One is that when the particle flow is falling, the particle diffusion mainly concentrates on the back of the particle flow. The other is that when particle flow collides with the contact surface, dust diffusion occurs in the area where the collision point is consistent with the outflow direction. According to the simulation results, a dust extraction device for dump truck is proposed to capture dust generated into the atmosphere. The influence of three representative factors: ambient temperature, shape of the dust collection port, fan speed on the performance of the dust extraction device is studied by means of orthogonal experimental design. The results show that the use of plain multiple slot suction port and higher fan speed can improve the dust removal effect and work efficiency of the dust collection device.

1. Introduction
Dump truck refers to a vehicle that unloads goods by hydraulic or mechanical lifting. It often works in conjunction with construction machinery such as excavators and loaders to form a transporting and loading production line, which is mainly used to transport goods in bulk[1]. Dump trucks are widely used as special vehicles for transportation due to automatic tilting of the loading carriage and the characters of saving unloading time and labor[2].

However, dump trucks will produce a large number of dust particles mainly including total suspended particulate matter (TSP), inhalable particulate matter (PM10), fine particulate matter (PM2.5) and other pollutions when dumping bulk materials such as sand and cinder in construction sites, mines and other places[3]. People who are exposed to above particles for a long time will not only increase the risk of cardiovascular, respiratory system and skin diseases, but also increase the incidence of cancer[4-6]. As more and more construction sites are built in urban areas, dust particles from construction sites not only have a negative impact on the cardiopulmonary function of construction workers, but also on the public health of surrounding residents.

A series of dust control equipment, such as dust gun, tower crane spray, sprinkler and so on, are mainly used in Chinese construction sites in order to solve this problem. However, the methods with high cost not only need to consume a lot of water resources but cannot deal with the dust in time and effectively. The humidified dust adhering to the ground causes secondary pollution[7-8].

A dump truck dust extraction device is designed in this paper in order to obtain better dust removal
effect. In the dump truck dumping process, the dust-laden air is sucked into the dust extraction device due to the negative pressure environment generated by the fan in the device. Dust is separated from air and retained in the dust removal device, and clean air is discharged from the exhaust port through the filtration of cyclone dust collector and dust collection bin. The device can be widely used in mining area, construction site and other construction occasions, which is expected to benefit 30 million employees in China who are directly or indirectly related to the industry, effectively prevent air pollution and reduce respiratory diseases caused by dust pollution.

2. Study on the material falling process of dump truck

2.1 Mathematical model

2.1.1 Model calculation assumption
The following assumptions should be made in the calculation of the model: (1) The gas phase in the gas-solid two-phase flow generated in the process of material falling is regarded as an incompressible continuous phase; (2) The particles are approximately regarded as spherical particles with uniform density; (3) The particle density is much higher than the gas density; (4) The volume fraction of particles is less than 10%; (5) The influence of temperature field, electromagnetic field and particle collision on the flow field is ignored.

2.1.2 Basic equation
Since this part mainly studies the gas-solid two-phase flow characteristics during the falling process of dump truck materials without heat transfer and chemical reaction, the governing equations include continuity equation, mass conservation equation and momentum conservation equation, whose specific formulas can refer to reference[9].

2.2 Physical model

2.2.1 Particle force analysis
Solid particles will be affected by gravity, drag force, Magnus force, pressure gradient force and so on when moving in the flow field. However, combining with the assumptions made above and comparing the various forces on the particles, the action of gravity and drag force is mainly considered in the particle motion. In addition, the influence of gravity and drag force is mainly considered in the falling process of the particle flow, and the force generated by collision and drag force are mainly considered in the process of particle colliding with contact surface[10]. The force analysis is shown in the Fig. 1.

![Force analysis during particle falling and collision with contact surface.](image)

2.2.2 Boundary conditions
The dump truck dumping process is assumed as follows: (1) Material outflow is mainly concentrated in
the dump truck compartment with an inclination of 45 to 50 degrees; (2) Ignore the influence of the geometry of the compartment on the material outflow and approximate the mass flow as a fixed value.

The geometric model can be obtained according to the above assumptions, which is composed of the inlet and the flow area. The particle inlet adopts velocity-inlet boundary. Realizable k-ε model is used for continuous phase. The pressure-velocity coupling equation adopts PISO equation. Since the volume fraction of particles is less than 10%, the DPM model is used for the particle phase. Three types of material particles are involved in this experiment, which are ash-solid, coal-ml and wood. And their densities are 600 kg/m³, 1400 kg/m³ and 700 kg/m³ respectively.

2.3 Analysis of simulation results and dust control

2.3.1 Analysis of simulation results

In this paper, particle trajectory effect diagrams showing particle residence time at different time are obtained by simulation. The dust diffusion phenomena during falling and collision phases of particle flow are analyzed, and the particle motion laws of particle flow are studied. For the convenience of explanation, it is specified in this paper that the directions facing the dump truck dumping materials is the front view direction, and the direction parallel to the outflow slope is the side view direction.

![Particle trajectory at 0.6 s](image)

As can be seen from Fig. 2, in the initial stage of falling, there is obvious particle scattering on the back of the outflow of particles, while the scattering of particles in front and on both sides of the outflow is not obvious. This is because most of the particles get the same initial velocity when they leave the dump truck box, while some particles get smaller or even no initial velocity due to the influence of external factors, thus forming the scattering particles on the back. Particles characterized by small quantity and mass stay in the air for a long time, which are easily affected by the air flow field generated by the falling of particle flow, thus forming inhalable dust.
Fig. 3. Particle trajectory at 1.2 s: (a), (b) and (c) show the particle trajectory of ash-solid, coal-ml and wood from the front view; (a1), (b1) and (c1) show the particle trajectory of ash-solid, coal-ml and wood from the side view.

As shown in Fig. 3, before the formation of the stack, the falling particle flow diffuses to the left and right sides of the contact point after colliding with the contact surface. Due to the initial outflow velocity of the main stream of particle flow from the right, the dust diffusion on the right side is more obvious than that on the left. The stack gradually forms as the particle flow falls, and the particle flow continues to diffuse outwards after colliding with the stack. When the particle flow collides with the stack, the air entrained by the particle flow during the falling process is released, and small particles next to the particle flow are carried into the air. Some particles in the main flow area and the stack diffuse into the surrounding air because the stack produces a reaction force when the particle flow collides with it. It can be seen from the figure that there is obvious diffusion phenomenon on the right side of the particle flow in the side view, while the particle diffusion phenomenon on both sides of the collision between the particle flow and the contact surface is weak in the front view.

2.3.2 Dust Control Analysis
From the above simulation results, it can be concluded that the dust generated in the dumping process of the dump truck mainly concentrates in two stages. One is that when the particle flow is falling, the particles in the back area of the particle flow are scattered, and the diffusion distance is short. Therefore, the ventilation and dust removal device can be installed near the particle flow collision point. The other is that when particle flow collides with the contact surface or the material pile, dust diffusion occurs obviously in the area where the collision point is consistent with the outflow direction, and the diffusion distance is relatively long. Since the dust diffusion phenomenon on both sides of the particle flow is relatively weak during the falling process and collision process of the particle flow, no dust removal device is required at this location.

3. Design and orthogonal experimental study on the performance simulation of dust extraction device for dump truck
Through the simulation analysis of the movement law of particle flow and dust diffusion phenomenon in the previous part, it can be obtained that when the dump truck dumps the material, the dust is mainly
generated in the back of the particle flow in the falling process and the area consistent with the direction of the outflow when the particle flow collides with the contact surface. Due to the long diffusion distance of the latter and the weak dust diffusion phenomenon on both sides of the particle flow in the direction of outflow, the dust extraction device designed in this paper is installed in the middle of the dump truck chassis, mainly for the dust scattered in the back of the particle flow during material falling.

3.1 Structure design and working principle of dust extraction device

![Dust extraction device structure](image)

The dust extraction device designed in this paper combines the characteristics of bag vacuum cleaner and cyclone dust collector. The purpose of separating dust and air can be achieved by using cyclone dust collector and dust filter bag. As shown in Fig. 4, the main body of the dust extraction device consists of a dust suction port, a connector, a cyclone dust collector, a dust collecting bin and a fan. The working principle is: using the internal motor installed on the fan to drive the fan to rotate at a high speed, which makes the interior of the dust extraction device show negative pressure or even vacuum state, and then inhale dust-bearing air from the dust suction port. Through dust filtration function of the cyclone dust collector and the dust filter bag installed in the dust collection bin, the air after twice dust removal enters the fan and is discharged from the outlet filter.

3.2 Physical model

The dust suction port is the core component of the dust extraction device, and the rationality of its design plays a decisive role in the dust suction effect. In this paper, three different structures of dust suction ports are designed, which are slot, plain opening and plain multiple slot. The structural schematic diagram of the design scheme is shown in Fig. 5. In order to eliminate the influence of suction area on the performance of the dust extraction device, the inlet area of each dust suction port remains the same.

![Structure schematic diagram of dust suction port](image)

3.3 Research on orthogonal experiment of vacuum cleaner performance simulation

Since there are many factors that affect the performance of the dust extraction device, this paper selects three representative factors: ambient temperature, shape of the dust collection port, and fan speed to study. If a comprehensive experimental method is adopted, although the influence of various factors on
the experimental results can be analyzed perfectly, this method requires a lot of time and energy. However, the orthogonal experimental method can make scientific and reasonable planning for multi-factor experiments, thus improving the efficiency and economy of experiments and reducing the amount of calculation[12].

3.3.1 Orthogonal experimental design
The number of factors and the range of changes at different levels should be determined first in the design of orthogonal experiments. The ambient temperature is designed into three levels: 263.15K, 283.15K and 303.15K respectively, representing the working environment of the dust extraction device in three different seasons. The influence of temperature changes on the working environment of the device is mainly reflected by the density and viscosity of the air. The fan speed is also set to three levels, 1000r/min, 2000r/min and 3000r/min respectively. According to the model design above, three different schemes for the shape of the dust suction port are designed, which are slot, plain opening and plain multiple slots. The orthogonal experimental design table of the performance of the dust extraction device is obtained, as shown in Table 1. It can be seen from the table that the probability of each factor and each level is equal, which indicates that the experimental scheme is feasible and reasonable.

| Test number | Ambient temperature A(K) | Suction port shape | Fan speed(r/min) |
|-------------|--------------------------|--------------------|-----------------|
| a           | 263.15                   | Slot               | 1000            |
| b           | 263.15                   | Plain opening      | 2000            |
| c           | 263.15                   | Plain multiple slot| 3000            |
| d           | 283.15                   | Slot               | 2000            |
| e           | 283.15                   | Plain opening      | 3000            |
| f           | 283.15                   | Plain multiple slot| 1000            |
| g           | 303.15                   | Slot               | 3000            |
| h           | 303.15                   | Plain opening      | 1000            |
| i           | 303.15                   | Plain multiple slot| 2000            |

3.3.2 Analysis of experimental results
This paper mainly analyses the velocity and pressure distribution of the internal flow field of the cyclone dust collector, which is the core working part of the dust extraction device.

![Fig. 6. Tangential velocity distribution of the cyclone dust collector at the y = 0 section.](image)
It can be seen from the Fig. 6 that the tangential velocity of the rotating airflow inside the flow field gradually increases with the increase of the radius. The centrifugal force on the particles also increases gradually, which helps the particles move towards the wall. The magnitude of tangential velocity under different working conditions varies greatly, but its distribution changes little. The tangential velocity of the dust cyclone collector in working conditions c, e, and g is the largest, which corresponds to the fan speed set by simulation. The result shows that fan speed is an important factor affecting the performance of dust extraction device. It can change the tangential velocity inside the cyclone dust collector, so as to achieve different dust separation effect.

The distribution of axial velocity indicates the rotating flow characteristics of the inner and outer layers of the dust collector. The gas has a downward axial velocity in the area close to the wall, forming a downward airflow that carries particles into the dust hopper. In the axial area of the dust collector, the axial velocity of the gas is upward, forming an upward airflow. The better the symmetry of the axial velocity distribution is, the better it is to stabilize the axial flow of airflow and improve the efficiency of dust removal. In the Fig. 7, it can be seen that the axial velocity distribution of the cyclone dust collector in working conditions c, f, and i has the best symmetry, which corresponds to the set dust suction port shape. The results show that the working efficiency of the dust extraction device can be increased by using the plain multiple slot dust suction port.

Fig. 7. Tangential velocity distribution of the cyclone dust collector at the y = 0 section.
Fig. 8. Total pressure distribution of the cyclone dust collector at the y = 0 section.

Total pressure is the superposition of static and dynamic pressure. It can be seen from the Fig. 8 that the distribution of total pressure along the radius has good symmetry. The total pressure gradually decreases as the radius decreases, and reaches the lowest point at the central vortex core. By analyzing the total internal pressure of the cyclone dust collector under nine different working conditions in the figure, it can be found that the pressure difference between the cylinder wall of the dust collector and the central vortex core in working conditions c, e, and g is the largest, followed by b, d and i and a, f and h is the smallest. This corresponds to the fan speed set by simulation. The results show that different pressure difference can be obtained by changing the fan speed. The higher the speed, the greater the pressure difference, which can provide more energy to the centrifugal force field, so as to improve the dust removal performance of the dust extraction device.

4. Conclusion
(1) Through the simulation of the dump truck dumping material process, it can be concluded that the dust generation is mainly concentrated in the two stages: particle flow falling and collision with the contact surface.

(2) The particle diffusion mainly concentrates on the front and back of the particle flow, and the former has a longer diffusion distance. There is no obvious particle diffusion on both sides of the particle flow throughout the process.

(3) Through the orthogonal experiment, it can be concluded that: the use of plain multiple slot suction port and higher fan speed can improve the dust removal effect and work efficiency of the dust collection device.

(4) Ambient temperature has little effect on the performance of the dust removal device.

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