Numerical simulation and field test of dust control effect of exhaust ventilation in fully mechanized face

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Abstract. In view of the ventilation status of xiaobaodang coal mine fully mechanized driving face, this paper puts forward the idea of using full extraction ventilation to solve the problem of pollution air leakage in long pressure short suction ventilation, which provides a new idea for dust control of fully mechanized excavation in xiaobaodang coal mine. Solid geometry model of fully mechanized driving face is established by SolidWorks. The influence of different distance between suction outlet and head-on and different air volume on dust migration distribution and dust control effect is analyzed by fluent. The results show that the best dust control effect is obtained when the air volume is set at 300m³/min and the distance between the suction outlet and the head-on is 5m. The dust concentration is lower than 10mg/m³ in the air duct side, 8m in the central section of the air duct and 16m in the height of the respiratory zone on the pedestrian side. The dust control effect is better at the side far away from the air duct. The measured results are consistent with the numerical simulation results. In addition, the optimized dust control method was verified on site, and the dust reduction efficiency at the driver's place and personnel walking position reached 62.8% and 82.8% respectively.

1. Introduction
Comprehensive excavation face is the main place of dust pollution. Through relevant research, it is found that the dust concentration of most fully mechanized excavation face without dust control measures can reach 1200 ~ 1500mg/m³, some even as high as 3000mg/m³. In recent years, due to the continuous development of tunneling equipment, the driving speed is greatly accelerated, and the dust pollution of fully mechanized excavation face is becoming more and more serious [1, 2]. At present, the most effective dust reduction measures for fully mechanized excavation face are ventilation and dust removal, which include: forced ventilation, extraction ventilation, long pressure short suction ventilation [3-4]. Although the forced ventilation can effectively blow away the gas and dust accumulation in the working face, it will also cause the dust to diffuse to the whole roadway. Long pressure and short suction ventilation has the advantages of the other two ventilation modes. However, it is found that the dirty air can not be completely enclosed in the working face, and some of it diffuses in the roadway, which greatly reduces the dust collection effect [5]. In addition, the long pressure short suction ventilation system needs multiple fans and supporting air ducts. With the advance of the driving face, the length of the air duct increases and the equipment is inconvenient to move. The reasonable extraction ventilation
can ensure that all dust is controlled in the head-on area, and all the dust is pumped away by the dust extraction duct, and the number of equipment is relatively small. In this paper, taking xiaobaodang coal mine as the engineering background, through the analysis of the influence of different exhaust volume and different distance between suction outlet and head-on on dust migration and distribution rule and dust control effect of working face under the condition of extraction ventilation, the optimal extraction ventilation and dust removal process parameters are determined, and the field application verification is carried out, which provides the basis for further optimization of extraction ventilation and dust removal system in fully mechanized excavation face.

2. Mathematical model

The movement of air and dust can be regarded as the movement of gas-solid two-phase flow. The standard k-ε equation was used to solve the problem where the air was treated as a continuous medium and the dust was treated as a discrete medium [6-7].

Where the \( k \) equation is:

\[
\frac{\partial}{\partial t} (\rho k) + \frac{\partial}{\partial x_j} (\rho k u_j) = \frac{\partial}{\partial x_j} \left[ \mu + \mu_t \frac{\partial k}{\partial x_j} \right] + G_k + G_\epsilon - \rho \varepsilon \frac{\partial Y}{\partial x_j} + S_k
\]

\( G_k = \mu_t S^2, S = \sqrt{\frac{\partial u_j}{\partial x_j}} \), \( S_0 = \frac{1}{2} \left( \frac{\partial u_j}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \)

The \( \varepsilon \) equation is:

\[
\frac{\partial}{\partial t} (\rho \varepsilon) + \frac{\partial}{\partial x_j} (\rho \varepsilon u_j) = \frac{\partial}{\partial x_j} \left[ \frac{\mu + \mu_t}{\sigma} \frac{\partial \varepsilon}{\partial x_j} \right] + \rho C_p S^2 - \rho \varepsilon \frac{\partial \varepsilon}{\partial x_j} + \varepsilon^2 \frac{\partial^2 \varepsilon}{\partial x_j \partial x_i} + C_1 \frac{\varepsilon}{k} \frac{\partial k}{\partial x_j} + S_\varepsilon
\]

\( C_1 = \max \left( 0, 0.43 \frac{u}{\varepsilon} \right) \), \( q = \frac{S}{\varepsilon} \)

\( \mu_t \) and \( \mu_t \) are the components of velocity in the x and y direction \( \left( m^2 \cdot s^{-1} \right) \), respectively. \( \rho \) is the airflow density \( \left( kg \cdot m^{-3} \right) \), \( \mu \) and \( \mu_t \) represent the viscosity coefficient \( \left( Pa \cdot s \right) \) in laminar flow and turbulence respectively \( \left( C_2 = 1.92, C_{14} = 1.44, \sigma_t = 1.0, \sigma_r = 1.2 \right) \). Since the air was assumed to be incompressible in this work, \( Y_m \) was taken to be 0.

The trajectories of the discrete phase particles were calculated using the discrete phase model by integrating and solving the differential equation of particle interaction in the Lagrangian coordinate system [8-9].

\[
m_p \frac{du_p}{dt} = \sum F = F_d + F_g + F_r + F_s
\]

Where \( m_p \) is the mass of the dust particles \( \left( mG \right) \), \( u_p \) is the movement speed of the dust particles \( \left( m \cdot s^{-1} \right) \), \( \frac{du_p}{dt} \) is the inertial force, \( \sum F \) is the sum of the force exerted on the dust particles \( \left( N \right) \), \( F_d \) is the resistance experienced by the dust particles \( \left( N \right) \), \( F_g \) is the force due to gravity acting on the dust particles, \( F_r \) is the buoyancy of the dust particles \( \left( N \right) \) and \( F_s \) are the other forces on the dust particles \( \left( N \right) \) such as Saffman force and Magnus force.

The resistance experienced by the dust particles, \( F_d \), can be expressed as:

\[
F_d = \frac{1}{2} C_d C_p A_p \rho (u - u_p) |u - u_p|
\]

Where \( C_d \) is the resistance coefficient, \( C_p \) is the dynamic shape coefficient, \( A_p \) is the particle windward area \( \left( m^2 \right) \) and \( u_p \) dust particle velocity \( \left( m \cdot s^{-1} \right) \).
When the dust particles move in turbulence, their motion path is affected by the turbulence. Assuming that the instantaneous fluctuation velocity of dust particles conforms to the Gaussian distribution [10]:

\[ u' = \zeta \sqrt{u'^2} \]  \hspace{1cm} (5)

Where \( \zeta \) is the random function of the normal distribution; \( \sqrt{u'^2} \) is the root mean square of fluctuating velocity (\( m \cdot s^{-1} \)).

In the \( k-\epsilon \) model, if the turbulence in the tunnel is isotropic, then [11]:

\[ \sqrt{u_x'^2} = \sqrt{u_y'^2} = \sqrt{u_z'^2} = \sqrt{\frac{2k}{3}} \]  \hspace{1cm} (6)

In order to calculate the random effect of turbulence on the particle diffusion, the instantaneous velocity can be integrated over a period of time. In other words, the particle trajectory equation can be obtained by integrating step by step in discrete time steps. For example, for the x direction, the particle's trajectory can be obtained from Eqn. (7):

\[ \frac{dx}{dt} = u_x \]  \hspace{1cm} (7)

By integrating along y and z directions, the movement trajectory of the dust particles in the three-dimensional space of the fully-mechanized face can be obtained [12].

3. Establishment of numerical calculation model and meshing

3.1. Modeling

In this paper, xiaobaodang coal mine fully mechanized face as the background, using three-dimensional Solidworks to establish geometric model. Because this paper only aims at the dust migration and diffusion law in the process of tunneling, it simplifies some equipment of roadway, including conveyor, belt and so on. The model is shown in Fig. 1. The working face is mainly composed of driving roadway, roadheader and extraction air duct. The working face size is 50m × 5m × 6m, and the following assumptions are made without affecting the simulation results:

1) The air in the coal roadway is regarded as an incompressible fluid, and the air flow density in the coal roadway is a constant;
2) The temperature in the tunnel is set as constant temperature by default;
3) The working face flow field is a steady flow field, independent of time.

![Fig. 1 Model of fully mechanized working face](image)

3.2. Meshing

The mesh is imported into the CFD model of fully mechanized mining face. In the simulation calculation, considering the complexity of the actual situation of the roadway, a better adaptive unstructured grid is adopted. A total of 3.057 474 million meshes were generated. Since the number of grids has a great influence on the accuracy of numerical simulation results, the mesh is adjusted adaptively to ensure small size distortion rate and angle distortion rate.
3.3. Parameter setting

The parameters of simulation parameters are set according to the actual situation of the site. The solver adopts the steady and absolute velocity when solving the ventilation dust field. Because the dust particles are affected by gravity in the roadway, the gravity acceleration is set in the simulation calculation. The specific parameters are shown in Table 1.

| Boundary condition          | Parameter setting | Boundary condition          | Parameter setting |
|-----------------------------|-------------------|-----------------------------|-------------------|
| Inlet Boundary Type         | velocity-inlet    | Diameter Distribution       | Rosin-Rammler     |
| Velocity Magnitude(m/s)     | -6.37             | Min. Diameter(m)            | 1e-06             |
| Outlet Boundary Type        | Outflow           | Max. Diameter(m)            | 1e-04             |
| Wall Shear Condition        | No Slip           | Mid. Diameter(m)            | 2e-05             |
| Interaction with Continuous | On                | Number of Diameters          | 150               |
| Material                    | Coal-hv           | Spread Parameter            | 3.5               |
| Total Flow Rate(kg/s)       | 0.01              | Turbulent Dispersion        | Discrete Random Walk Model |

4. Influence of different ventilation parameters on dust control effect

In order to study the influence of different parameters on the dust control effect of working face under the condition of extraction ventilation in fully mechanized excavation face, this paper analyzes the dust control effect under the conditions of the air volume of 200 m$^3$/min, 300 m$^3$/min and the distance between suction outlet and head-on is 5m, 6m, 7m, 8m, 9m, 10m, and obtains the ventilation parameters with the best dust control effect.

4.1. Analysis of dust concentration distribution in central section of air duct

Fig. 2 Dust concentration distribution in the central section of air duct when the distance between suction outlet and head-on is 5m

Fig. 3 Dust concentration distribution in the central section of air duct when the distance between suction outlet and head-on is 10m

Fig. 2 and Fig. 3 show the dust concentration distribution in the central section of the air duct when the distance between the suction inlet and the head-on is 5m and 10m respectively. It can be seen from the figure that: 1) the dust movement direction of the working flour always diffuses from the head-on to the rear. Due to the limited range of negative pressure, the negative pressure ability on the same side of the principle wind is weakened, and the dust diffusion distance is far. 2) When the distance between the air outlet and the head-on is fixed, the greater the air volume is, the better the dust control effect of the
working face is; when the air suction amount is fixed, the closer the suction outlet is to the head-on, the better the comprehensive dust control effect of the working face is. 3) In order to clearly show the dust concentration control effect of working flour, the minimum scale shown in Fig. 2 and Fig. 3 is set as 10mg / m³, so the dust concentration in the blue area in the figure is lower than 10mg / m³. In order to better control the dust diffusion, the distance between the suction outlet and the head-on and the air volume of the suction outlet should be reasonably matched.

Fig. 4 shows the distribution of dust concentration in the axial section of the air duct of the working face when the suction outlet is 5m, 7m and 10m away from the head-on when the air volume is 300m³ / min. It can be seen from the figure that: 1) the dust diffuses from the head-on to the rear. Due to the influence of the exhaust air, the dust diffuses more seriously on the side of the reflux area, and the diffusion phenomenon is weak at the side of the exhaust duct; 2) under the same air volume, the different distance between the suction outlet and the head-on has obvious influence on the dust distribution of the working flour. When Lg = 5m, the farthest dust diffusion distance is 8m; when Lg = 7m, the farthest dust diffusion distance is 15m; when Lg = 10m, the farthest dust diffusion distance is 10m. In addition, in order to clearly show the dust concentration control effect of working flour, the minimum scale is set as 10mg / m³, so the dust concentration in the blue area in the figure is lower than 10mg / m³. By comprehensive comparison, it can be found that when Lg = 5m, the dust can work The effect of surface dust control is the best.

Fig. 4 Dust concentration in the central section of the air duct of the working face when the ventilation rate is 300m³ / min

4.2. Analysis of dust concentration distribution along the height of lateral respiratory zone

Fig. 5 Dust concentration distribution along the pedestrian side of the working face when the ventilation rate is 300m³ / min
Fig. 6 Dust concentration distribution along the pedestrian side of working face when the ventilation rate is 200m$^3$/min

Fig. 5 and Fig. 6 show the dust concentration distribution along the height of the respiratory zone on the pedestrian side when the air volume of the ventilation tube is 300m$^3$/min and the dust concentration distribution along the pedestrian side when the ventilation volume is 200m$^3$/min. It can be seen from the figure that: 1) the dust concentration in the process of dust diffusion from head-on to back shows a trend of decrease increase decrease. The main reason for this kind of county magistrate is that the dust suction port is relatively high, the negative pressure range is limited, and the space occupied by the road header blocks the negative pressure air flow, so the dust near the road header tends to increase. 2) With the increase of the ventilation rate, the dust concentration and the backward diffusion distance of dust are significantly reduced. When the ventilation rate is 200m$^3$/min, the maximum dust concentration is 1532mg/m$^3$, and the farthest backward diffusion distance is 28m. When the ventilation rate is 300m$^3$/min, the maximum dust concentration is 1210mg/m$^3$ and the farthest backward diffusion distance is 23m. 3) Comprehensive consideration, the best dust control effect can be obtained when the air volume of the fully mechanized driving face is set at 300m$^3$/min and the distance between the suction outlet and the head-on is 5m.

4.3. Verification analysis of downhole measurement

Fig. 7 Layout of dust concentration test on site
In order to verify the accuracy of the numerical simulation analysis results, the actual measurement of dust concentration in coal mine was carried out according to the numerical simulation results. The site dust concentration test layout is shown in Figure 7. Six measuring points are arranged on the right sidewalk (5, 1.5, 3), (5, 1.5, 6), (5, 1.5, 9), (5, 1.5, 12), (5, 1.5, 15), (5, 1.5, 18). Each measuring point is tested three times and its average dust concentration is taken. The results are shown in Figure 8. The comparison between the field test results and the numerical simulation results shows that the two results show the same trend, which indicates the reliability of the numerical simulation results. The site setting of the exhaust air volume of 300m$^3$/min and the distance between the suction outlet and the head-on 5m also show better dust control effect. However, the measured results are slightly higher than the numerical simulation results, which may be due to the appropriate simplification of the working face in the process of establishing the numerical model. In addition, the underground dust source points are complex, and the dust source points are not set completely in the actual simulation process.

### 4.4. Dust fall effect analysis

In order to verify the effectiveness of the optimization of the air volume and the distance between the suction outlet and the head-on in the exhaust ventilation mode on the dust control effect, the underground dust reduction effect was analyzed. When the air volume of the extraction type air duct is set to 300m$^3$/min and the distance between the suction outlet and the head-on is 5m, the dust concentration of the whole dust is tested at the driver's position (3, 1.8, 6) and the personnel's walking place (5, 1.5, 10). The test results are shown in Table 2. It can be seen that the optimized exhaust ventilation dust removal method has good dust control effect, and the dust reduction efficiency at the driver's place and personnel walking position reaches 62.8% and 82.8%, respectively. The field application contrast effect diagram is shown in Fig 9 and Fig 10.

**Table 2. Comparison of dust reduction effect**

| Position        | Original concentration | Concentration after dust control | Dust fall efficiency |
|-----------------|------------------------|----------------------------------|---------------------|
| Driver's position | 1620mg/m$^3$          | 602 mg/m$^3$                     | 62.8%               |
| Personnel location | 1186 mg/m$^3$        | 203 mg/m$^3$                     | 82.8%               |
5. Conclusion
In this paper, the influence of different air volume and different distance between suction outlet and head-on on dust control effect of fully mechanized excavation face is studied:

The dust always accumulates near the head-on of fully mechanized excavation face, and the dust concentration can reach 1500mg / m³. Due to the influence of negative pressure air flow, the dust will diffuse backward, and the dust concentration far away from the negative pressure air duct is higher than that at the negative pressure air duct side.

Due to the effect of negative pressure air duct, the dust will move backward to the suction outlet after a distance. The distance between the suction outlet and the head-on and the amount of exhaust air have obvious influence on the dust control effect of working flour. When the distance between the suction outlet and the head-on is fixed, the dust control effect is better by increasing the amount of exhaust air; when the distance between the suction outlet and the head-on is fixed, the dust control effect is better. When the air volume is set at 300m³ / min and the distance between the suction outlet and the head-on is 5m, the dust control effect of the working face is the best. The farthest diffusion of dust in the central section of the air duct is 8m, and the farthest dust diffusion is 16m at the height of the respiratory zone on the pedestrian side.

The measured dust concentration of the working flour shows that the measured results and the numerical simulation results are consistent, which verifies the reliability of the numerical simulation results. In addition, the optimized dust control method was verified on site, and the dust reduction
efficiency at the driver's place and personnel walking position reached 62.8% and 82.8% respectively. There are no other control measures for dust control in this study. If other control dust reduction measures are adopted, such as spray dust suppression, dust removal curtain, bubble breaking and dust removal, the dust control effect will be better.

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