Effects of Air Outlet Position and Air Speed on Airflow and Dust Field Distributions

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Abstract. To meet the actual demands on ventilation and dust removal in mine heading faces and to reduce the potential safety threats and pollution risks of dust, this study investigates the migration and distribution trends of airflow and dust fields at different air outlet positions and air speeds under scenarios using forced ventilation and long-forced-short-exhaust ventilation techniques at the heading face under continuous mining operation, which is accomplished in the engineering context of Xiaobaodang Coal Mine by a combination of two-phase flow analysis and finite element simulation. As the results reveal, the return air speeds exhibit a "rising-falling-stable" trend at different air outlet positions and inlet air speeds. Appropriate increase of inlet air speed is effective in covering the front corner area and in improving the dust distribution in the roadway. Dust concentration on the return air side is markedly higher than on the air duct side, with distribution primarily in the front section. In the case of forced ventilation for the roadway having a large cross-sectional area of 22 m², reasonable dust distribution on the return air side can be ensured when the air duct outlet is 10 m away from the front and the inlet air speed is 11 m/s. In the case of long-forced-short-exhaust ventilation, reasonable settings are a 15 m distance of air duct outlet from the front and a 9 m/s speed of inlet air.

1. Introduction
As one of the five major hazards in coal mining, the coal dust problem in underground coal mines not only threatens the safety of underground production greatly, but also poses huge health risks, such as pneumoconiosis, to underground operators [1-2]. Currently, ventilation and dust removal technology is often applied to achieve fast long-distance, large-section tunneling, where dust generated by tunneling and cutting is dispersed primarily by injection of fresh air with the ventilation system comprising local fans and air ducts. The Coal Mine Safety Regulations (2016) stipulated that for fully mechanized excavation faces, the total dust concentration should not be higher than 4 mg/m³, while maximum and minimum air speeds should be 4 and 0.25 m/s, respectively [3]. Excessively high dust concentration and excessive air speed at heading faces affect the underground working environment and the health of operators seriously. In the engineering context of heading faces in the Xiaobaodang Coal Mine operated by Shaanxi Coal and Chemical Industry, this study investigates the migration and distribution trends of roadway air speeds and dust fields in the forced and long-forced-short-exhaust ventilation modes under continuous mining operation. The findings of this study are profoundly meaningful for the dust pollution...
control and dust hazard reduction at heading faces and for the improvement of operator working environment.

2. Creation and solution of computational model

2.1. Theoretical analysis

Dust generated at heading faces moves by the action of airflow, which belongs to the research area of gas–solid two-phase flow [4]. Since the volume fraction of dust at heading faces is considerably lower than 10%, the Euler-Lagrange method is employed for airflow–dust coupling solution. Initially, airflow fields are solved in the Euler coordinate system. On this basis, dust particles are solved in the Lagrange coordinate system with the DPM model.

Tunneling roadway is regarded as a constant temperature domain, while the thermal radiation of coal wall is disregarded. Simulation computation of airflow and dust field should conform to the fundamental principles of fluid mechanics, i.e. the conservation equations of mass and momentum. Herein, they are embodied as the continuity equation and the N–S equation.

The continuity equation is expressed as [5]:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i) = 0$$  \hspace{1cm} (1)

The N–S equation is expressed as [6]:

$$\rho \frac{du}{dt} = \rho f - \nabla p + \mu \nabla^2 u$$  \hspace{1cm} (2)

Where \(\nabla^2 = \frac{\partial^2}{\partial x_1^2} + \frac{\partial^2}{\partial x_2^2} + \frac{\partial^2}{\partial x_3^2}\). Airflow at the heading face is regarded as an incompressible ideal fluid, so \(\nabla \cdot u = 0, \mu = 0\). Hence, the following simplification can be made:

$$\frac{du}{dt} + (u \cdot \nabla) = f - \frac{1}{\rho} \nabla p + \nu \nabla^2 u$$  \hspace{1cm} (3)

2.2. Creation of geometric and mesh models

According to the actual conditions of continuous mining face in Xiaobaodang Coal Mine, the 12CM15-10D continuous miner is simplified into two parts: the frame and the cutting system. The roadway is 40 m long, while the excavation width and height are 5.8 and 3.8 m, respectively. The pressure and exhaust ducts are located at the top corners of roadway side walls. With a diameter of 1.0 m, these air ducts are 0.7 m away from the side walls and 3.0 m away from the floor [7]. Roadway geometric models are built in scenarios of forced and long-forced-short-exhaust ventilations at the heading face by using the DM module of ANSYS Workbench. Meshing is performed with more adaptable unstructured meshes in the ANSYS Workbench Meshing module, whose cell size is set to 0.2 m. Fig. 1 presents the created models in the case of forced ventilation.

2.3. Setting of model parameters and boundary conditions

In consideration that the ventilating airflow at the heading face is isotropic homogeneous turbulence, and that the curvature of streamline near the heading front is relatively large, the steady state
computation of air fields is performed by SIMPLEC algorithm with the Realizable k – ε model. Meanwhile, the numerical simulation analysis of dust migration and distribution trends is accomplished based on the Euler–Lagrange method. Tabs. 1 and 2 detail the relevant boundary conditions and discrete phase model (DPM) parameters. Air speed at the air duct inlet is included as one of the variables, whose values are set to 7, 8, 9, 10, 11 and 12 m/s, respectively.

**Tab. 1 Boundary condition settings**

| Boundary condition       | Setting          |
|--------------------------|------------------|
| Inlet boundary type      | Speed inlet      |
| Inlet turbulence intensity| 3.08%            |
| Inlet hydraulic diameter | 1.0 m            |
| Outlet boundary type     | Flow outlet       |
| Wall shear condition     | No slip          |

**Tab. 2 DPM parameter settings**

| DPM                        | Setting                                      |
|----------------------------|----------------------------------------------|
| Inter-phase coupling       | Enabled                                       |
| Coupling frequency         | 20                                            |
| Particle size distribution | Rosen–Lammler distribution                   |
| Minimum particle size      | 1e-06 m                                       |
| Maximum particle size      | 1e-04 m                                       |
| Median particle size       | 6.03e-05 m                                    |
| Particle size number       | 10                                            |
| Distribution index         | 1.62                                          |
| Mass flow rate             | 0.0036 kg/s                                   |
| Turbulence dispersion model| DRW model (stochastic tracking approach)      |

3. Simulation analysis concerning the effects of air outlet position and air speed on airflow field

3.1. In forced ventilation mode

Changes in the return air speed with distance are comparatively analyzed at different air outlet positions and inlet air speeds, which is achieved by selecting the pedestrian breathing height along the return air side of roadway (X= 5 m, Y= 1.6 m, Z= 0-40 m). Fig. 2 displays the comparison results.

![Fig. 2 Changes in return air speed with distance under forced ventilation](image)

(a) 5-m distance from the front       (b) 10-m distance from the front

As is clear from Fig. 2, when the air duct outlet is 5 m and 10 m away from the front, the air speeds on the return air side exhibit a "rising then falling" trend at different inlet air speeds affected by the continuous miner at the heading face, which eventually stabilize at around 0.5 m/s, showing a fundamentally consistent pattern. Moreover, at higher inlet air speeds, the corresponding return air speeds at the pedestrian position are higher. Compared to a 5-m distance of air outlet from the front, the return air speed corresponding to a 10-m distance is higher in the first 10 m, while is lower after 10 m.
3.2. In long-forced-short-exhaust ventilation mode

In Fig. 3, variations of air speed on the exhaust duct side with distance are illustrated at different air outlet positions and inlet air speeds under the long-forced-short-exhaust ventilation mode. As is clear, due to the presence of continuous miner, marked changes in air speed are noted when the exhaust duct is around 5 m and 15 m from the front after injection of airflow into the front face. At a 10-m distance of air outlet from the front, the inlet air speed is rather high, and the corresponding air speeds on the exhaust duct side increase slightly within 15 m, which then show certain fluctuations affected by eddy currents, thereby easily leading to reentrainment of dust. In contrast, at a 15-m distance of air outlet from the front, the air speeds corresponding to higher inlet air speeds are somewhat higher.

![Fig. 3](image)

(a) 10-m distance from the front
(b) 15-m distance from the front

Fig. 3 Changes in air speed with distance on the exhaust duct side under long-forced-short-exhaust ventilation

4. Simulation analysis concerning the effects of air outlet position and air speed on dust field

4.1. In forced ventilation mode

Similarly, by selecting the pedestrian breathing height along the return air side of the roadway (X= 5 m, Y= 1.6 m, Z= 0-40 m), a comparative analysis is conducted concerning the dust concentration distribution at pedestrian breathing height on the return air side at different air outlet positions and inlet air speeds. Fig. 4 illustrates the comparison results.

![Fig. 4](image)

(a) 5-m distance from the front
(b) 10-m distance from the front

Fig. 4 Dust distributions in the horizontal sections of the return air side under forced ventilation
To reflect the effects of parameter changes on the dust distribution intuitively, the dust concentration values along the pedestrian way on the return air side are extracted for comparative analysis, as shown in Fig. 5. According to a combination of Figs. 4 and 5, the dust concentration is distinctly higher on the return air side than on the air duct side, and is distinctly higher in the front section of the return air side than in the back section. Moreover, there are even dust accumulations at the right area of front face and the tail of continuous miner. At a 5-m distance of air duct outlet from the front, the optimal inlet air speed for ventilation and dust removal is 9 m/s, and the corresponding average dust concentration on the return air side is 171 mg/m³. When the air duct outlet is 10 m away from the front, the optimal inlet air speed for ventilation and dust removal is 11 m/s, and the corresponding average dust concentration on the return air side is 156 mg/m³. Given the risk of dust accumulation at a 5-m air outlet distance from the front, we can select a distance of 10 m under forced ventilation, as well as an inlet air speed of 11 m/s, in order to ensure the lowest dust concentration at the pedestrian position.

4.2. In long-forced-short-exhaust ventilation mode

In Fig. 6, dust concentration distributions at pedestrian breathing height on the exhaust duct side are presented at different air outlet positions and inlet air speeds under long-forced-short-exhaust ventilation for heading face.
Similarly, dust concentration values along the pedestrian way on the exhaust duct side are extracted for quantitative analysis, as shown in Fig. 7. According to a combination of Figs. 6 and 7, little dust is found in the middle and back sections of the roadway, which is distributed primarily on the right and rear of continuous miner, and shows a small area of accumulation at the front right corner. There is a risk of dust dispersion in the middle section of roadway at higher inlet air speeds. At a 10-m distance of air duct outlet from the front, the optimal inlet air speed for ventilation and dust removal is 12 m/s, and the corresponding average dust concentration on the return air side is 108 mg/m³. Meanwhile, when the air duct outlet is 15 m (approximately 3.5\sqrt{S}, S denotes the roadway sectional area) away from the front, the optimal inlet air speed for ventilation and dust removal is 9 m/s, the sectional dust distribution at pedestrian breathing height is reasonable, and the average dust concentration on the return air side is 94 mg/m³. Thus, a 15 m distance of air outlet from the front can be selected under long-forced-short-exhaust ventilation, as well as an inlet air speed of 9 m/s, in order to ensure the reasonable dust concentration at the pedestrian position.

5. Conclusions
(1) Return air speeds exhibit a "rising then falling" trend at different air outlet positions and inlet air speeds, which eventually stabilize. Moreover, higher inlet air speeds correspond to higher return air speeds, exhibiting a fundamentally consistent pattern. Dust concentration is distinctly higher on the return air side than on the air duct side. Primary distribution of dust is found in the front section of the return air side, which even shows a small area of accumulation at the front right corner.
(2) In forced ventilation mode, a 10 m distance of air duct outlet from the front and an 11 m/s speed of inlet air for ventilation and dust removal can ensure a lowest dust concentration at the pedestrian position on the return air side, with a value of 156 mg/m³.
(3) In the case of long-forced-short-exhaust ventilation, reasonable dust distribution on the return air side can be ensured when the air duct outlet is 15 m away from the front and the inlet air speed for ventilation and dust removal is 9 m/s, with an average dust concentration of 94 mg/m³ at lowest.

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