The movement rule of rust in primary airflow on fully mechanized heading faces and its numerical simulation

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Abstract

Ventilation mode is applied in most coal mines in China for dedusting on fully-mechanized coal faces. On the heading faces, the cutting head of roadheader generates primary airflow of dusts when it works. While, the ventilation flow for discharging dusts produces secondary airflow that moves dusts. Owing to secondary airflow is the major power source of dust movement, how dusts move on heading faces without ventilation flow and the movement rule were investigated. Based on fluid mechanics and by using the discrete phase model in FLUENT software, numerical simulation was performed for the movement of discrete-phase dusts of different sizes on the heading faces. The simulation results indicated that the maximum moving distance of dusts was within 0.5 m to the heading faces. The conclusion provided significant theoretical basis for dedusting on heading faces in coal mines.

Keywords: Dusts,Roadheader, Fully-mechanized heading faces, Primary airflow, Secondary airflow

1 Introduction

When roadheader tunnels on the fully-mechanized heading faces in coal mine, dusts pollute the surrounding environment to 60 m or even 150 m [1]. There are two factors that cause the expansion of the pollution scope, namely, the primary airflow and secondary airflow. The former refers to the airflow generated by the movement of cutting head of roadheader when it rotates and cuts coal on local fully-mechanized heading faces. The later is the ventilation flow on the heading faces of local roadway. The paper focused on the influences of primary airflow on the pollution scope of dusts in fully-mechanized excavating.

Presently, the research on underground primary airflow in China mainly focuses on the macro treatment of dust source. For examples, professor Haiqiao Wang in Hunan University of Science and Technology applied air curtain based technique to isolate dusts in primary airflow on fully-mechanized heading faces and obtained preferable effect [2]; associate professor Jianzhuo Zhang in Liaoning Technical University investigated the influences of fan speed, the diameter of dedusting wind tube and the variation of outlet pressure on the moving track of dust particles that moved by primary airflow [3]; by adopting the No. 1528 fully-mechanized heading face in Gequan coal mine of Hebei Jinniu Energy Resources Co., LTD as the research object, Ronghua Liu et al. in Central South University conducted numerical simulation for the movement of underground airflow [4]. In other countries, the movement rule of primary airflow is merely studied on ground, and the rule underground has not been explored. The research in China and abroad shows that the previous studies promote the research on the movement rule of primary airflow in coal mine underground, while desired achievements have not been obtained. Therefore, it is of great significance for revealing the movement rule of dusts under the effect of primary airflow on the heading faces in coal mines.

2 Dust source on roadway heading face

According to the provisions of International Organization for Standardization (ISO), dusts are suspended solids larger than 75 μm in diameter. The dusts on the roadway heading faces mainly come from two sources: the dusts generated in the primitively crustal movement. They stay in uncut coal and fly upwards in primary airflow that generated as the cutting head of the roadheader rotates; the other dusts are produced in the shear and compression of coal when the cutting head rotates and in the broken of cut coal when it falls onto the ground, and fly upwards and diffuse on roadway heading faces with the effect of primary airflow. In roadway, all the pulvation actions that turn static dusts to suspended ones in the air are primary pulvation actions [5]. The pulvation airflows in roadway mainly are the energy that transmitted to surrounding airflows by the rotation of the cutting head of the roadheader. As primary pulvation action causes air pollution in local roadway, the research on dusts diffusion in roadway is of important significance for the treatment of air pollution in underground roadway.

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3 Dust movement in primary airflow

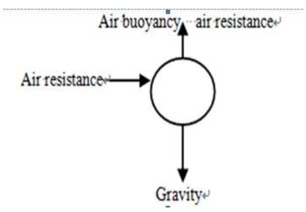


FIGURE 1 Stresses on dusts

Suppose that the dust is a uniform sphere without interspace. As demonstrated in Figure 1, the stress of dust movement is analyzed. It shows that, the dust is under the actions of four forces, including air resistance, gravity of itself, air buoyancy, and molecule diffusion force and the force of airflow that moves the dust. Dusts that larger than 10 μm in diameter are mainly affected by the first three forces, those diameter ranges in 10~2.5 μm are affected by all the above forces, and those less than 2.5 μm in diameter are mainly under the action of molecule diffusion force and the force of airflow that moves the dust.

When dusts move horizontally at an initial velocity υ_0 under mechanical effect, the speed decelerates due to air resistance. The movement rule of the dusts is inferred using the following formula [6]:

$$\frac{1}{6}\pi d_c^3 \rho_c \frac{dv}{dt} = -3 d_c \mu v \pi \,, \qquad (1)$$

where $\frac{dv}{dt}$ is accelerated velovity, m/s^2; μ is the dynamic viscosity of air, Pa·s (μ =1.81074155×10^{-5} Pa·s at 20^{0}C); d_c is the diameter of the dusts, m; ρ_c is the density of dusts, kg/m^3.

The final velocity of the dusts moving horizontally is:

$$v = v_0 e^{-t/\tau} \,. \qquad (2)$$

The distance of the dusts moving in a time period of t is:

$$S_s = \int_0^t v dt = \int_0^t v_0 e^{-t/\tau} dt = \tau v_0 (1 - e^{-t/\tau}) \,, \qquad (3)$$

where $\tau = \frac{d_c^2 \rho_c}{18\mu}$; v_0 is the velocity of the dust, m/s.

According to the stresses acted on the dust and the calculation results of formulae (1), (2) and (3), the movements of coal dust particles of 100 μm, 50 μm, 10 μm, 5 μm and 2.5 μm in diameter and 1,500 kg/m^3 in density were analyzed. The results are illustrated in Table 1.Table 2 displays the horizontal moving speeds of dust particles of different diameters in different time period.

TABLE 1 Horizontal moving distances of dusts particles of different diameters

Diameter (μm)	τ (s)	Horizontal distance at 0.01s (m)	Horizontal distance at 1 s (m/ s)	Horizontal distance at 2 s (m/ s)	Horizontal distance at 3 s (m/ s)	Limit (m)
100	4.6×10-2	9.0×10-2	4.6×10-1	4.6×10-1	4.6×10-1	4.6×10-1
50	1.2×10-2	7.0×10-2	1.2×10-1	1.2×10-1	1.2×10-1	1.2×10-1
40	7.4×10-3	6.0×10-2	7.4×10-2	7.4×10-2	7.4×10-2	7.4×10-2
10	4.63×10-3	4.0×10-2	4.63×10-2	4.63×10-2	4.63×10-2	4.63×10-2
5	1.16×10-4	1.16×10-3	1.16×10-3	1.16×10-3	1.16×10-3	1.16×10-3
2.5	2.9×10-5	2.9×10-4	2.9×10-4	2.9×10-4	2.9×10-4	2.9×10-4

TABLE 2 Horizontal moving speeds of dusts of different diameters with different times

Diameter (μm)	τ (s)	Horizontal speed at 0.01 s (m/ s)	Horizontal seed at 0.1 s (m/ s)	Horizontal spped at 1 s (m/ s)	Limit (m/ s)
100	4.6×10-2	8.05	0.114	0	0
50	1.2×10-2	3.51	0.002	0	0
40	7.4×10-3	2.59	0.000014	0	0
10	4.63×10-3	1.15	0	0	0
5	1.16×10-4	0	0	0	0
2.5	2.9×10-5	0	0	0	0

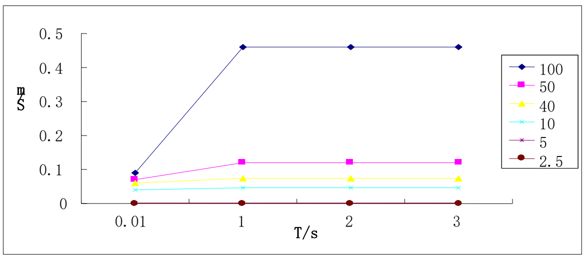


FIGURE 2 Curves of horizontal moving distance of dusts of different diameters corresponding to Table 1

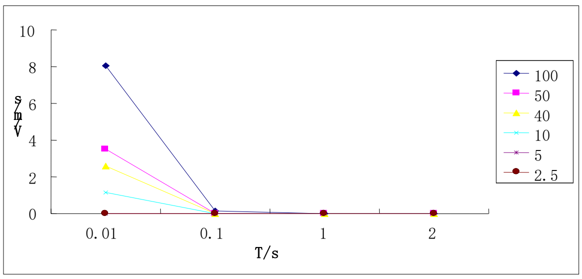


FIGURE 3 Curves of horizontal moving speeds of dust particles of different diameters in different time periods corresponding to Table 2

Table 1 and Table 2 indicate that, after the dusts horizontally moving at an initial speed of v_0=10m/s for 0.01

s, the speed reduces to zero sharply. Even maximum dust merely moves a maximum distance of 4.6×10^{-1} m. These reveal that, even if under the action of mechanical force, the dusts are not able to diffuse in the roadway alone [7, 8].

Compared with velocity of dusts, which are under the action of primary airflow, the minimum speed of airflow (0.2~0.3m/s) in roadway is generally tiny. It indicates that the movement of dusts is mainly dominated by airflow in roadway. When the dusts diffuse as stroked by air molecules in Brownian motion, owing to the dust mass is much larger than that of air molecule, the dusts merely move 1.2×10^{-2} m in 1 s by diffusing. Therefore, compared with airflow speed in roadway, the effect of molecule diffusion force can be ignored [9].

4 Numerical simulation and analysis for dust movement in primary airflow

4.1 CONSTRUCTION OF MATHEMATICAL MODEL

Based on kinetic theory of discrete phase and the conservation law of continuous phase, the following controlling equations are obtained:

Mass conservation equation is

$$\rho\frac{\partial v_i}{\partial x_i}=0. \tag{4}$$

For incompressible fluid, $\frac{\partial \rho}{\partial t}=0$.

Balance equation of momentum is:

$$\rho\frac{\partial v_i}{\partial t}+\frac{\partial}{\partial x_j}\left(\rho v_i v_j\right)=\frac{\partial p}{\partial x_i}+\mu\frac{\partial^2 v_i}{\partial x_j^2}+\rho g_i, \tag{5}$$

where p is static pressure, μ is coefficient of dynamic viscosity, and g_i is the volume force of gravity in I direction.

K-epsilon turbulence model and K equation is:

$$\rho\frac{\partial k}{\partial t}+\frac{\partial}{\partial x_j}\left(\rho v_j k\right)=\frac{\partial}{\partial x_j}[\frac{\mu}{\sigma_k}-\frac{\partial k}{\partial x_j}]+G-\rho\varepsilon. \tag{6}$$

ε equation is:

$$\rho\frac{\partial \varepsilon}{\partial t}+\frac{\partial}{\partial x_j}\left(\rho v_j \varepsilon\right)=\frac{\partial}{\partial x_j}[\frac{\mu_t}{\sigma_\varepsilon}-\frac{\partial \varepsilon}{\partial x_j}]+\frac{\varepsilon}{k}(c_1 G-c_2\rho\varepsilon). \tag{7}$$

G is the term that generates the kinetic energy of turbulent fluctuation, $G=\mu_t(\frac{\partial v_i}{\partial x_j}+\frac{\partial v_i}{\partial x_i})\frac{\partial v_i}{\partial x_j}$; μ_t is the coefficient of turbulent viscosity, $\mu_t=\frac{c_\mu \rho k^2}{\varepsilon}$; c_1, c_2, c_μ, σ_k, and σ_ε are empirical constant, among which c_1 =1.42, c_2 =1.8, c_μ =0.09, σ_k =1.0, and σ_ε =1.3.

4.2 SET OF BOUNDARY PARAMETER CONDITIONS

Based on the selected underground data, 2-dimension mathematical model of the movement of dusts of different diameters was constructed using GAMBIT software and meshed [10]. Afterwards, the data exported from GAMBIT were imported in FLUENT. Suppose that the underground airflow is multiphase flow of dusts and air, in which the air is continuous phase and the dusts are discrete phase, the turbulent flow is incompressible viscous flow, and k-ε turbulent flow model was adopted [11-13]. According to the measured data, the inlet boundary conditions of dusts of different diameters were determined, at a temperature of 20℃. The boundary conditions and the parameters of dust source were set in Table 3 and Table 4.

TABLE 3 Major parameters of boundary conditions

Boundary conditions	**Parameter set**
Air speed at roadway exit (m/s)	0.35
Hydraulic diameter (m)	3.1
Turbulence intensity (%)	2.7
Type of inlet boundary	Velcocity-Inlet
Type of outlet boundary	OUTFLOW

TABLE 4 Major parameters of dust source

Particle source	**Parameter set**
Diameter distribution	Rosin-rammler distribution
Minimum diameter (m)	1.0×10-6
Maximum diameter (m)	1.0×10-4
Initial velocity (m/s)	0
Dust density (kg/m3)	4.8×10-3
Mass flow rate (kg/s)	9.8×10-3

4.3 ANALYSIS OF SIMULATION RESULTS

The models of dust movement simulated are demonstrated in the following figures.

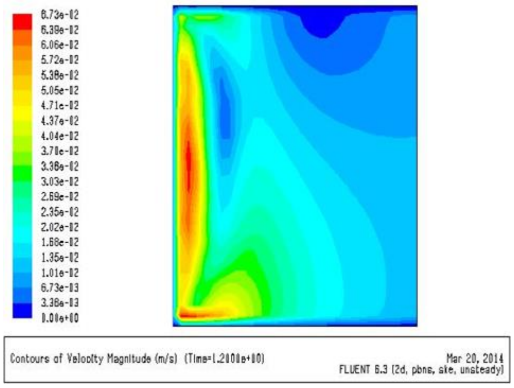


FIGURE 4 Cloud picture of the moving speed of dispersed-phase dusts

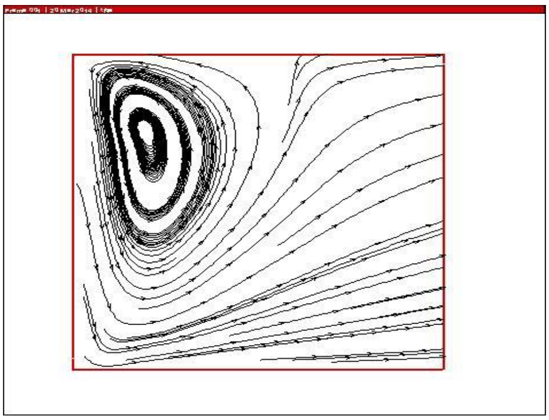
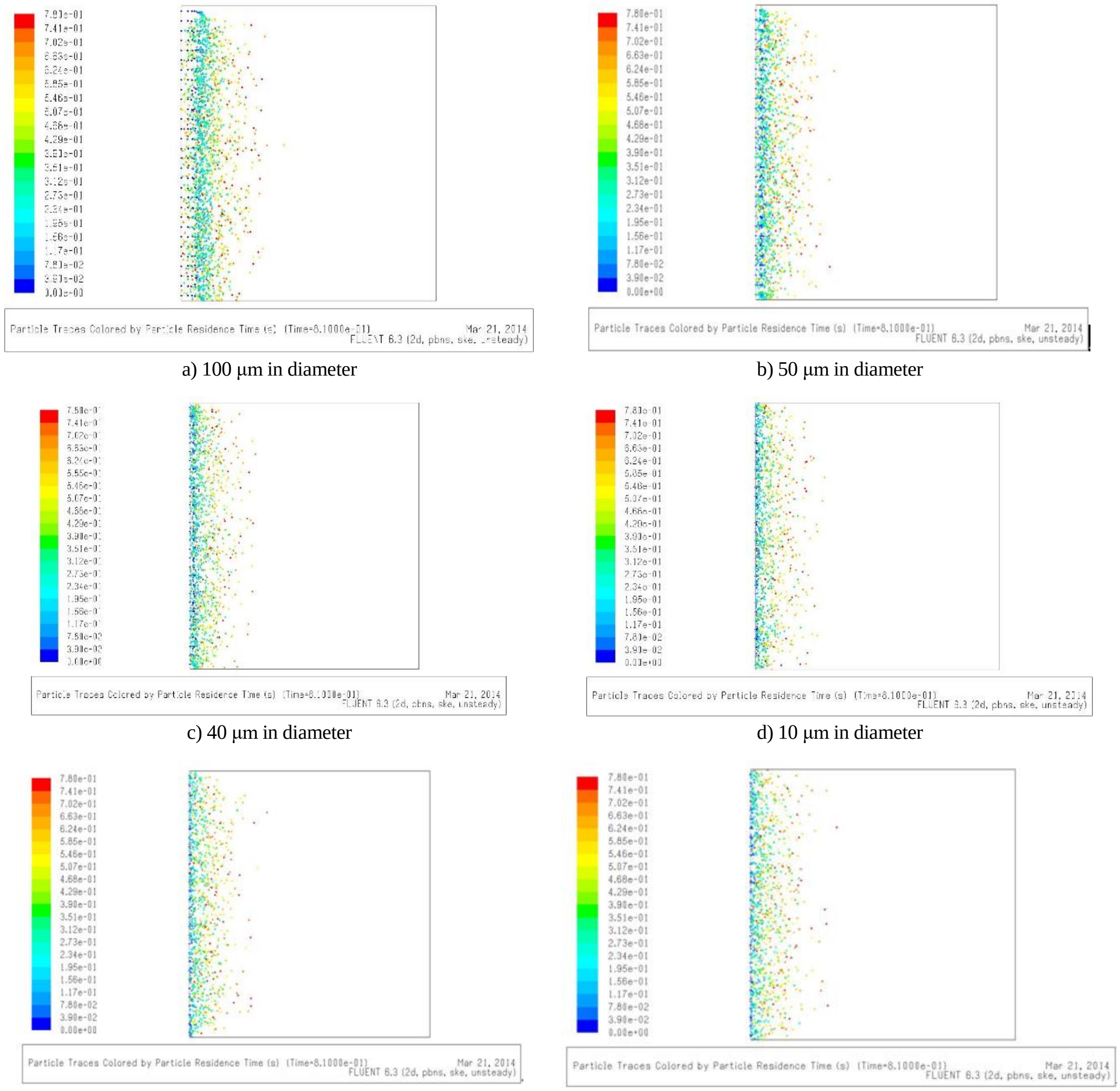


FIGURE 5 Vectorgraph of the moving speed of dispersed-phase dusts



a) 100 μm in diameter

b) 50 μm in diameter

c) 40 μm in diameter

d) 10 μm in diameter

e) 5 μm in diameter

f) 2.5 μm in diameter

FIGURE 6 Moving tracks of dust particles of different diameters

Figure 4 shows the moving speed of dust particles on the heading face. It is observed that the dust particles move from the heading face into the roadway at 10 m/s initially. Then under the combined action of air resistance, gravity of themselves, and buoyancy, the speed reduce gradually. In a very short period initially, the speed of dust particles decreases sharply, and the dusts fall on the roadway floor afterwards. While, due to the effect of secondary airflow on the heading face, minority of the dust particles that have fallen on the roadway floor fly upwards again, diffuse out of the roadway, and are diluted finally. Figure 5 is the vectorgraph of the moving speed of dust particles. It illustrates that, after moving downwards, the dusts generated by the cutting of roadheader on heading face fly upwards under the effect of secondary airflow. The reentrainment of dusts pollutes the fully-mechanized heading face. Owing to the existence of airflow, there is vortex flow in the upper roadway of the cutting point of heading face. The generation of vortex flow threatens the safety mining production underground. Therefore, to avoid the damage caused by vortex flow, certain ventilation and dust-collection measures have to be adopted to treat the dusts in upper roadway and effectively avoid or reduce the production of vortex flow. The moving tracks of dust particles of different diameters were illustrated in Figure 6. The movement of dust particles of 100 μm, 50 μm, 40 μm, 10 μm, 5 μm, and 2.5 μm in diameters was simulated respectively. Then by fitting the dispersed and continuous phases, the simulations results were obtained, as displayed in Figure 6 (a), (b), (c), (d), (e), and (f). The comparison of the moving tracks of different dusts indicates that dust particles of large diameter fall on the roadway floor earlier than those of little diameter due to the gravity influence; while owing to the little gravity, some dusts of small diameter disperse to the roadway and gradually diffuse outside the roadway under the secondary airflow of ventilation. Furthermore, secondary airflow poses less effect on dusts of large diameter than those of small diameter. All these indicate that the detection and treatment for dusts of small diameter (particularly respirable dusts) are critical for preventing disaster accidents caused by dusts on heading faces in coal mine.

The simulation results revealed that tiny dusts didn't have self-movement ability; instead of making the dust fly and diffuse into the entire roadway, the energy that primary pulvation action generated merely polluted the air of local areas near to the cutting head. What caused the diffusion and pollution of dusts for the whole roadway is mainly the secondary airflow of ventilation, that was, the airflow formed by the forced ventilation in the roadway. The secondary airflow carried local dust-containing air to flow in the whole roadway and therefore diffused the dusts to every corner of the underground roadway. The faster the secondary airflow speed, the more distinct the effect was.

5 Conclusions

Following conclusions were drawn in the paper:

(1) The movement of dust relies on airflow. Under the effect of primary airflow that generated when the cutting head of roadheader cuts coal on fully-mechanized heading faces, dusts merely diffuse within 0.5 m. Therefore dusts are unable to diffuse to the whole roadway in primary airflow.

(2) The expansion of dust pollution can be prevented by setting air curtain, which separates dusts from the ventilation airflow, between the cutting head of roadheader and the rocker arm, and sucking up the dusts using dust collector.

(3) In dust prevention on the underground heading faces, air pollution of flying dusts caused by secondary airflow of ventilation can be avoided by frequently watering and cleaning the roadway.

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References

[1] LU Zhongliang, FAN Xiaoli, XIAO Yaning 2008 Experimental Analysis and Numerical Simulation on the Inside Inhaling and Outside Pressing Particle Collector *China Safety Science Journa* **18**(10) 99-103

[2] WANG Haiqiao, LIU Ronghua. 2000 Simulative Experiment and application of Dust-suppression Air Curtain in Fully Mechanized Face. *Mining Safety&Environmental Protection* **27**(2), 13-17

[3] ZHANG Jianzhuo, ZHU Tianzi, GAO Meng, ctc. 2011 Parameter Optimization and Numerical Simulation of Dust-collecting and Dedusting System with Air Curtain in Fully Mechanized Excavation Face *China Safety Science Journal* **21**(4), 128-131.

[4] Liu Ronghua, LiXibing, Shi Shi-liang. 2009 Study on the Influence of Outlet Angle of Air Curtain at Full-mechanized Work Face on Its Dust-isolating Effectiveness *China Safety Science Journal* **19**(12) 128-134

[5] *Deleted by CMNT Editor*

[6] SUN San-xiang, CHANG Qing, LI Jie, DONG Bo 2006 Study on Control of Coal Dust of Coal Trains Travelling Along the Daqin Railway *Journal Of The China Railway Society* **28**(2), 21-25

[7] HONG Bo, LIN Bo-rong, WANG Bing, LI Shu-hua 2012 Optimal design of vegetation in residential district with numerical simulation and field experiment *Journal of Central South University* (3), 688-695

[8] *Deleted by CMNT Editor*

[9] YAO Yujing,CHENG Weimin,NIE Wen,etc. 2011 Numerical Simulation of Dust Concentration Distribution in a Fully Mechanized Heading Face *Mining Safety & Environmental Protection* **38**(3), 21-25

[10] YUN Xia, CHENG Xue-fei, JIN Yao-lan, YU Shuai, XU Jian-yun 2013 Numerical Simulation and Experimental Study of the Nozzle Flapper Electro-pneumatic Pressure Servo-valve Based on Fluent *Hydraulics Pneumatics & Seals* (9),10-13

[11] LIU Yi, JIANG Zhong'an, CAI Wei, etc. 2007 Numerical simulation of the dust movement rule in fully-mechanized coal faces. *Journal Of University Of Science And Technology Beijing* **29**(4), 351-353

[12] *Deleted by CMNT Editor*

[13] MO Fan, YU Zhongming, WU Guiyi. 2012 Numerical simulation of dust movement law and concentration distribution in return airway with sudden change of cross-section *China Coal* **38**(1), 107-111

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