Theoretical research on migration and settlement of dust in roadway

J Wang¹, Y Zheng*² and N Jia¹

¹ Department of Engineering Physics, Tsinghua University, Beijing, P.R. China
² College of Safety Engineering, North China Institute of Science and Technology, Langfang, P.R. China

Abstract. At present, most scholars use the mathematical model of FLUENT software to simulate migration and settlement process of dust, and tend to focus only on the graphical simulation results. For intermediate operation principle and process is not very clear, simulation results of commercial software will easily lead to distortion of simulation results. Based on this, the migration and settlement process of flowing dust in return airway of coal face has carried on the further analysis and research in this paper, and the main factors affecting the dust migration and settlement are analyzed comprehensively. At the same time, according to the law of mass conservation, a three-dimensional mathematical model of migration and settlement of flowing dust is established. The purpose is to reveal the migration and settlement law of flowing dust.

1. Introduction

Coal mine dust is the general name of all kinds of fine solid particles produced in the production process of coal mine. Dust is one of the five major disasters in coal mine, which not only brings great threat to underground safety production, but also seriously endangers the health of underground workers. Long-term inhalation of mine dust by underground workers can easily cause pneumoconiosis. At the same time, dust will reduce the visibility of the workplace and increase the occurrence of industrial accidents. Mine dust itself will explode under certain conditions, and will also participate in gas explosion, which can cause serious harm. Dust will also accelerate mechanical wear and shorten the service life of the instrument. With the development of mechanization, intensification and high efficiency of coal mining technology, dust control has become an important part of coal mine safety production [1-4].

Coal dust generally has two states of plankton and deposition, which will change under certain conditions. For example, under the action of its own gravity, some of the planktonic dust will settle into deposited dust, and deposited dust will fly up under the action of high wind speed or shock wave to become floating state. The upper limit concentration of coal dust explosion is 1500-2000 g/m³ and the lower limit concentration is 45 g/m³. There are too many floating dust in the air, so that the dust concentration reaches the explosion limit, which will cause coal dust explosion. If the concentration of floating dust is in the range of 300-400 g/m³, the explosive power is the strongest. Once the coal dust explosion occurs, it will cause immeasurable loss and damage to mine equipment and personnel, which is extremely destructive. At the same time, the underground dust produced by the explosion will be discharged from the ground again, causing air pollution [5-8].
There are many dust producing places in the mine production process, and almost all operations can produce dust. The coal mining face is the largest dust producing place in the mine. In the absence of effective measures, the dust concentration in coal face can reach 5000-10000mg/m³. Because the air flow is blown into the return airway from the intake airway through the coal mining face, the dust in the coal mining face will be inevitably brought into the return airway by the air flow. Such a high concentration of floating dust is bound to gradually settle in the return airway, which becomes a potential safety hazard in coal dust explosion[9-10]. All of wind speed, particle size distribution and dust concentration affect dust deposition. Therefore, it is necessary to give a comprehensive and systematic relationship among these factors. The study of dust migration and settlement law and theory in the return airway of coal mining face has important reference value for the study of calculating the required air volume for dust removal, arranging dust test points in coal mining face, optimizing dust measurement method and preventing of dust explosion scientifically.

2. Analysis of the influencing factors of dust migration and settlement
Assuming that there is a point M in the dust concentration field in the return airway of coal mining face, the enclosed surface F which contains M is chosen arbitrarily. The enclosed area is D, and the enclosed volume is V. n is the unit normal vector of the enclosed surface F, which points outward. Hexahedral unit body with side lengths of Δx, Δy and Δz respectively is shown in Figure 1.

Figure 1. Hexahedral unit body in return airway

Based on the analysis of the dust concentration change of the hexahedron unit body in the return airway of the coal mining face, it is concluded that the main factors affecting the mass change of the unit body are: the diffusion effect caused by the difference of dust concentration, the air flow effect and the sedimentation effect of dust gravity.

The dust migration and settlement process in return airway satisfies the mass conservation law, that is, the sum of the dust mass difference $M_1$ caused by the difference of dust concentration, the dust mass difference $M_2$ caused by air flow, and the dust mass difference $M_3$ caused by gravity sedimentation is equal to the dust mass change $M_4$ in the unit body. The control equation is expressed in formula (1).

$$M_1 + M_2 + M_3 = M_4$$

2.1. The diffusion effect caused by the difference of dust concentration
The dust diffusion flux is:

$$q_x = -k \frac{\partial C}{\partial x}$$

Where, $q_x$ is the dust diffusion flux along the x-axis, kg/m²/s; $k$ is the dust diffusion coefficient, m²/s; $C$ is the dust concentration in the unit body, kg/m³; and $\partial C / \partial x$ is the dust concentration gradient along the x-axis, kg/m⁴.
The mass difference of dust diffusing in and out of the unit body along the positive direction of the $x$-axis is:

\[ q_x dydzdt - q_{x+dt} dydzdt \]
\[ = q_x dydzdt - \left( q_x + \frac{\partial q_x}{\partial x} dx \right) dydzdt \]
\[ = - \frac{\partial q_x}{\partial x} dxdydzdt \]
\[ - \frac{\partial}{\partial x} \left( -k \frac{\partial C}{\partial x} \right) dxdydzdt \]
\[ = k \frac{\partial^2 C}{\partial x^2} dxdydzdt \] (3)

Similarly, the dust mass differences of dust diffusing in and out of the unit body along the positive direction of $y$-axis and $z$-axis are:

\[ q_y dxdzdt - q_{y+dy} dxdzdt = k \frac{\partial^2 C}{\partial y^2} dxdydzdt \] (4)
\[ q_z dxdydt - q_{z+dz} dxdydt = k \frac{\partial^2 C}{\partial z^2} dxdydzdt \] (5)

Then, the dust mass difference $M_1$ caused by the difference of dust concentration diffusing into and out of the unit body is:

\[ M_1 = k \frac{\partial^2 C}{\partial x^2} dxdydzdt + k \frac{\partial^2 C}{\partial y^2} dxdydzdt + k \frac{\partial^2 C}{\partial z^2} dxdydzdt \]
\[ = k \left( \frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial y^2} + \frac{\partial^2 C}{\partial z^2} \right) dxdydzdt \] (6)

2.2. The driving force of air flow

The mass difference of dust bringing into and out of the unit body by air flow along the positive direction of the $x$-axis is:

\[ Cudydzdt - \left[ Cu + \frac{\partial (Cu)}{\partial x} dx \right] dydzdt = - \frac{\partial (Cu)}{\partial x} dxdydzdt \] (7)

Similarly, the dust mass differences of dust bringing into and out of the unit body by air flow along the positive direction of $y$-axis and $z$-axis are:

\[ Cvdxdzdt - \left[ Cv + \frac{\partial (Cv)}{\partial y} dy \right] dxdzdt = - \frac{\partial (Cv)}{\partial y} dxdydzdt \] (8)
\[ Cwdxdt = \left[ Cw + \frac{\partial (Cw)}{\partial z} dz \right] dxdt = - \frac{\partial (Cw)}{\partial z} dxdydzdt \] (9)
Then, the dust mass difference $M_2$ bringing into and out of the unit body by air flow is:

$$M_2 = -\frac{\partial(Cu)}{\partial x} dxdydzdt - \frac{\partial(Cv)}{\partial y} dxdydzdt - \frac{\partial(Cw)}{\partial z} dxdydzdt$$

(10)

2.3. The sedimentation caused by gravity

The dust mass difference $M_3$ falling in and out of unit body caused by gravity sedimentation is:

$$M_3 = \left[ v_d C + \frac{\partial(v_d C)}{\partial z} dz \right] dxdydt = \frac{\partial(v_d C)}{\partial z} dxdydzdt$$

(11)

Where, $v_d$ is dust deposition velocity, m/s.

2.4. The change of dust quality in micro body

Dust mass change $M_4$ in unit body is:

$$M_4 = \left( C + \frac{\partial C}{\partial t} dt \right) dxdydz - C dxdydz = \frac{\partial C}{\partial t} dxdydzdt$$

(12)

Substituting equations (6), (10), (11) and (12) into equation (1) gives the control equation of dust concentration:

$$k \left[ \frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial y^2} + \frac{\partial^2 C}{\partial z^2} \right] dxdydzdt + \frac{\partial(v_d C)}{\partial z} dxdydzdt$$

$$- \left( \frac{\partial(Cu)}{\partial x} + \frac{\partial(Cv)}{\partial y} + \frac{\partial(Cw)}{\partial z} \right) dxdydzdt = \frac{\partial C}{\partial t} dxdydzdt$$

(13)

After simplification, it can be concluded that:

$$k \left[ \frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial y^2} + \frac{\partial^2 C}{\partial z^2} \right] + \frac{\partial(v_d C)}{\partial z} - \left( \frac{\partial(Cu)}{\partial x} + \frac{\partial(Cv)}{\partial y} + \frac{\partial(Cw)}{\partial z} \right) = \frac{\partial C}{\partial t}$$

(14)

3. The definite conditions

3.1. The initial condition

The initial condition of formula (14) is:

$$t = 0, C = C_0$$

(15)

Where, $C_0$ is the initial dust concentration in the roadway, kg/m$^3$.

3.2. The boundary conditions

Assuming $\Gamma_1$ is the entrance boundary of the return airway, $\Gamma_2$ is the exit boundary, $\Gamma_3$ is the front wall, $\Gamma_4$ is the rear wall, $\Gamma_5$ is the roof, and $\Gamma_6$ is the floor, the calculation area and boundary schematic diagram of dust concentration in return airway is shown in Figure 2.

Figure 2. The calculation area and boundary sketch map of dust concentration field in return airway
Dust enters the roadway from the boundary $\Gamma_1$. Since the dust concentration at the boundary surface can be measured, this paper takes the boundary $\Gamma_1$ as the first type of boundary condition, which can be expressed as:

$$C|_{\Gamma_1} = C_1$$

(16)

Where, $C_1$ is the dust concentration of the boundary $\Gamma_1$, kg/m$^3$.

The dust hardly settles in the long distance of the roadway, so it is considered that there is no falling dust at the exit boundary, and the dust flows out of the boundary surface together with airflow. Therefore, the exit boundary $\Gamma_2$ is taken as the second type of boundary condition in this paper, which can be expressed as:

$$k \frac{\partial C}{\partial x}|_{r_2} = 0$$

(17)

The surrounding walls of the roadway have fallen dust caused by diffusion effect, so the boundary $\Gamma_3 \sim \Gamma_6$ are taken as the third type of boundary conditions in this paper, which can be expressed as:

$$\begin{align*}
    k \frac{\partial C}{\partial y}|_{r_3, r_4} &= k' C|_{r_3, r_4} \\
    k \frac{\partial C}{\partial z}|_{r_5, r_6} &= k' C|_{r_5, r_6}
\end{align*}$$

(18)

Where, $k'$ is the proportional coefficient, m/s.

4. **The three-dimensional mathematical model of dust migration and deposition**

The governing equation and the definite solution conditions of dust concentration constitute a complete three-dimensional mathematical model of dust migration and settlement in the return airway. Namely:

$$\begin{align*}
    C &= C_0 (t = 0) \\
    C|_{r_1} &= C_1 \\
    k \frac{\partial C}{\partial x}|_{r_1} &= 0 \\
    k \frac{\partial C}{\partial y}|_{r_3, r_4} &= k' C|_{r_3, r_4} \\
    k \frac{\partial C}{\partial z}|_{r_5, r_6} &= k' C|_{r_5, r_6}
\end{align*}$$

(19)

5. **Conclusions**

(1) The main factors affecting dust migration and settlement in the return airway of coal mining face are diffusion effect caused by dust concentration difference, air flow effect and dust gravity settlement effect.
(2) According to the mass conservation law, considering the mass change in the unit body caused by the diffusion effect, air flow effect and gravity effect, the control equation of dust concentration field in the return airway of coal face is established.

(3) The initial and boundary conditions of the control equation of dust concentration field in the return airway are determined, and a complete three-dimensional mathematical model of dust migration and settlement in the return airway is established. The model theoretically presents the relationship among these influencing factors and reveals the migration and settlement process of dust, which has important reference value for preventing of dust explosion scientifically.

Acknowledgments

This work was supported by China Postdoctoral Science Foundation (Grant No. 2018M631482), Beijing Municipal Natural Science Foundation (Grant No. 9194027), and China Postdoctoral Science Foundation (Grant No. 2019M650750). The authors are deeply grateful to these supports.

References

[1] Geng F, Zhou F B and Luo G 2014 Min. Saf. Environ. Protec. 41 85-9
[2] Chen J S, Jiang Z A and Jiang L 2014 J. Chin. Coal Soc. 39 135-36
[3] Jiang Z A, Chen J S, Wang J J, Niu W and Gao Y 2012 J. Chin. Coal Soc. 37 659-63
[4] Jia H Y and Ma Y D 2007 Environ. Pollut. Ctrl. 29 767-70
[5] Cheng W M, Liu X S, Ruan G Q, Guo Y X and Wang G 2009 J. Chin. Coal Soc. 34 203-07
[6] Cheng W M, Liu W, Nie W, Zhou G and Cui X F 2010 J. Shandong Univ. Sci. Tech. (Nat. Sci.) 29 77-83
[7] Tan C, Jiang Z A, Wang M and Chen Y 2015 J. Chin. Coal Soc. 40 122-27
[8] Tan C, Jiang Z A, Chen J S and Wang P 2014 J. Univ. Sci. Tech. Beijing 36 70-3
[9] Shi X X, Jiang Z A and Chu Y Y 2005 J. Saf. Sci. Tech. 1 41-3
[10] Jiang Z A, Chen J S and Niu W 2012 J. Univ. Sci. Tech. Beijing 34 976-81