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Diffusion and pollution of multi-source dusts in a fully mechanized coal face

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ABSTRACT

In order to provide theoretical guidance for dust prevention and treatment, as well as environmental protection for mines, we investigated the diffusion and pollution of multiple sources in a fully mechanized coal face using CFD-DPM based airflow-dust coupling method, and analyzed the distributions of dust particle diameter at different positions. Results show that, the air was mainly leaked from three positions in the mining area, 6 m away from the air inlet on the leeward side, the position where the hydraulic prop was moved and the middle part of the shearer. A high-velocity airflow zone was formed around the shearer's front roller, with airflow velocity up to 2.2 m/s. The dusts produced by the advancing support were superposed with the dusts from the roller's coal cutting, and a high-concentration dust zone with a length of approximately 2 m was formed at the front roller, with dust concentration as high as 3000 mg/m^3. Within 40 m from the air outlet, a great number of dusts larger than 70 μm settled. Finally, the field measured results of airflow and dust concentration verified the accuracy of the simulation of dust diffusion and pollution behaviors in the fully mechanized coal face.

1. Introduction

Comprehensive mechanized coal mining gains increasing popularity in modern coal mines with continuous improvement of mechanization, which results in large amount of dust in the mining face. According to statistics, the dust produced in mining faces accounts for 60%–80% of that in the whole mine (Nie et al., 2017a; Nie et al., 2018; Ni et al., 2018a; Meng, 2013; Zheng et al., 2012; Zhang et al., 2018; Liu et al., 2018a; Cheng et al., 2009). Massive amount of dust produced in different procedures of coal mining, such as coal cutting and support advancing, which would spread leeward from the dust source aided by airflow. This leads to high concentration of dusts in the working area and thus threatens the physical heath of miners. The measured results indicate that local dust concentrations in the mining face reaches up to 3000 mg/m^3, which far exceeds the national hygienic standard. These dusts of high concentration pose a great challenge to the environmental protection related to coal mines (Tang et al., 2015; Nie et al., 2017b; Ni et al., 2018b; Liu et al., 2018b; Cheng et al., 2017; Zhou et al., 2018; Xu et al., 2013). High-concentration dusts would not only trigger explosion accidents (Amyotte, 2014; Li et al., 2016; Zhi et al., 2015), but also pollute the underground working environment and impair workers' physical and psychological health (Zhou et al., 2017; Jiang et al., 2017; Nie et al., 2016; Fan et al., 2018). According to the notification by the National Health and Family Planning Commission of the People's Republic of China, 26873 new pneumoconiosis cases were reported in 2014, which increased by 3721 in one year. 25317 patients suffering from pneumoconiosis were miners, who accounted for 94.21% of the total pneumoconiosis cases (Hua et al., 2018a; 2018b; Hu et al., 2017). Evidently, high concentration of dusts in coal mining industry did cause tremendous harm to workers. More in-depth knowledge of the diffusion and pollution rules of the dusts from multiple sources in mines will be of scientific and practical significance to dust prevention and treatment in the working faces as well as environment protection in mines.

International scholars mainly used the following three methods to investigate the diffusion and pollution rules of the dusts from multiple sources in fully mechanized coal faces; namely, similarity experiment, field measurement and numerical simulation. Specifically, similarity experiments were mainly conducted

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on scaled simulation models. Tan et al. designed an experimental model for a fully-mechanized face in Tongxin Coal Mine and investigated the concentration distribution pattern of the dusts with different moisture contents produced in coal cutting, support movement, coal caving and transportation (Tan et al., 2015). Shi et al. also constructed an experimental model for analyzing the variation of dust concentrations during coal cutting under different wind velocities (Shi et al., 2008). However, the simplified structures and conditions in their simulation models caused large deviations from the actual field conditions. Nie et al. performed field measurements of concentration distribution pattern of PM2.5 dusts at a working face during coal mining (Nie et al., 2013). Liu et al. also measured the variation of dust concentration along the path during downwind and upwind coal cutting in a fully mechanized coal face (Liu et al., 2006). Field measurements also show a series of shortcomings. The measurements are easily affected by production and geographic conditions, and therefore, the measured data are unstable and far from being comprehensive. Field measurements are generally adopted to validate the accuracy of similarity experiments and numerical simulations. By contrast, numerical simulations can accurately represent the airflow field and the diffusion behaviors of the dusts from different sources. Moreover, this technique is efficient, convenient and affordable, with excellent capability in visualizing the results. Owing to these advantages, numerical simulations now have been widely applied to investigate the diffusion-induced pollution rules of the dusts from multiple sources in the fully mechanized coal face in international academia circles.

Currently, international scholars have obtained many valuable results in the diffusion and pollution rules of the dusts from multiple sources in fully mechanized coal faces using numerical simulations. Based on gas-solid two-phase flow theory, Liu et al. established a dust diffusion model in coal cutting and investigated the distribution rules of airflow field and dust concentration around the shearer in a fully mechanized coal face (Liu et al., 2009). Using Eulerian-Lagrangian method, Jiang et al. simulated dust diffusion in a fully mechanized coal face, and analyzed the effects of wind velocity, speed of scraper conveyor and roller's rotating speed on the diffusion of the dusts produced in coal cutting (Tan et al., 2014). Through numerical simulation, Yao et al. examined the effects of different mining procedures and parameters on dust diffusion and its concentration distribution (Yao et al., 2014a; 2014b; Yao et al., 2015). Using FLUENT (a computational fluid dynamics software), Alam et al. simulated dust distribution and diffusion in a roadway under working conditions (Alam, 2006). Ren et al. applied computational fluid dynamics (CFD) model to analyze dust diffusion in longwall fully mechanized coal face (Ren et al., 2013). Patankat et al. conducted simulations on the spatial distribution characteristics of dust particles with different Stokes numbers in the airflow field using LES (Patankar and Joseph, 2001).

Admittedly, the existing investigation on this topic can be further improved by considering at least the following issues. Firstly, underground equipments significantly affect the diffusion of dusts by interfering the air flow, and these effects were not taken into account in the previous physical models which were oversimplified with regard to the actual site conditions. Secondly, the existing investigation mainly focuses on the mining areas but seldom considers the effects of air leakage in goaves, which certainly exists in the goaf and would affect the dust diffusion in the whole working face (Tang et al., 2015; Luan et al., 2017; Yao et al., 2015). Thirdly, the dust particles in a fully mechanized coal face are characterized by small sizes and massive amounts. In the previous studies regarding airflow-dust coupling diffusion rules, the dust diffusion rules were mainly analyzed at a macro-scale (i.e., based on the measured dust concentration results), other than a combination of dust concentration and size at a micro-scale. Because of the above issues, the acquired dust diffusion and pollution rules cannot accurately reflect the practical onsite conditions. This further influences the reliability of the suggestions on dust prevention and control in fully mechanized coal faces as well as environmental protection concluded from the simulations.

Based on the practical conditions of equipment installed on site, a physical model of the fully mechanized coal face was established, which includes a mining region, a goaf, a material roadway and a transportation roadway, and can thus accurately represent the field conditions. Moreover, the multiple dust sources were set in this fully mechanized coal face, and the numerical simulation data were processed using CFD-POST. Meanwhile, in combination with the field measured results, the multiple-source dust diffusion and pollution rules were determined with better accuracy. The basic characteristics of dusts, including concentration variations and along-the-way settling and diffusion behaviors, were investigated at both macro- and micro-scales. The present research can provide theoretical bases for dust prevention and control as well as environmental protection in coal mines, which further protects the physical and psychological health of miners.

2. Model and simulation parameter settings

2.1. Mathematical model

According to the characteristics of airflows and dusts in a fully mechanized coal face, the airflow was treated as a continuous phase and the dust was regarded as a discrete phase. There exist many models for the solution of turbulent airflows, in which $k-\varepsilon$ model is most widely applied in industrial flow problems and thus was used in this study (Ren and Chen, 2006; Xin et al., 2017; Wu et al., 2007).

The continuity equation for gas can be written as :

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_j}\left(\rho v_j\right) = 0 \tag{1}$$

Based on the law of mass conservation, the following expression can be acquired (Zuo, 2014):

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} + \frac{\partial(\rho w)}{\partial z} = 0 \tag{2}$$

The momentum equation can be written as :

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}\left(\rho u_i u_j\right) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[(\mu+\mu_t)\left(\frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j}\right)\right] \tag{3}$$

The energy equation can be written as (Liu et al., 2018c):

$$\frac{\partial}{\partial x_i}(\rho v_i T) = -\frac{\partial}{\partial x_i}\left[\left(\frac{\mu}{p_r} + \frac{\mu_i}{\sigma_i}\right)\frac{\partial T}{\partial x_i}\right] + \frac{q}{c_p} \quad i = 1/2/3 \tag{4}$$

The kinetic energy equation of turbulent fluctuation (also known as k-equation) can be written as (Nie et al., 2015; Wang et al., 2017):

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho u_i k) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + G_k - \rho\varepsilon \tag{5}$$

The energy dissipation rate equation of the kinetic energy of turbulent fluctuation (also known as ε-equation) can be written as:

$$\frac{\partial}{\partial t}(\rho\varepsilon) + \frac{\partial}{\partial x_i}(\rho u_i \varepsilon) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + \rho C_1 E\varepsilon - \rho C_2 \frac{\varepsilon^2}{k+\sqrt{v\varepsilon}} \tag{6}$$

According to Newton's second law, the equilibrium equation of the interactions between the discrete particles can be written as (Wu, 2008):

$$m_p \frac{dU_p}{dt} = F_d + F_f + F_g + F_x \tag{7}$$