Advanced Powder Technology xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Advanced Powder Technology

journal homepage: www.elsevier.com/locate/apt

Original Research Paper

Effects of radial air flow quantity and location of an air curtain generator on dust pollution control at fully mechanized working face

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A R T I C L E I N F O

Article history:
Received 7 October 2016
Received in revised form 31 March 2017
Accepted 25 April 2017
Available online xxxx

Keywords:
Air curtain dust control
Airflow migration states
Dust diffusion law
Numerical simulation

A B S T R A C T

To better understand the effects of radial air flow quantity and the location of air curtain generator on dust pollution control, the 2–109$_2$ fully mechanized working face in Xinzhi coal mine (Huozhou Coal Electricity Group Co., Ltd., Shanxi, China) was numerically simulated in the present study. A full-scale physical model of the working face was established; then, based on airflow-dust particle two-phase flowing characteristics, the k-ε-Θ-k_p mathematical model was constructed. The comparison between simulation results and field measurements validated the model and the parameter settings. Furthermore, the effects of ventilation parameters on airflow migration and dust diffusion were numerically investigated using FLUENT. The results show that the increase of the radial air flow quantity (denoted as φ) and the distance of the air curtain generator from working face (denoted as d_w) is beneficial to the formation of a dust-control air curtain. At a constant d_w, the dust diffusion distance (denoted as D) decreases with the increase of φ. At a constant φ, D decreases with the increase of d_w when a dust-control air curtain is formed; otherwise, the increase of d_w leads to the increase of D. By analyzing the simulation results, the optimal ventilation parameters for 2–109$_2$ fully mechanized working face and those working faces under similar production conditions are determined as: $\varphi = 240–270\ \mathrm{m^3/min}$ and $d_w = 20–30$ m.

1. Introduction

Coal serves as an important type of basic energy in China. Recent years have witnessed continuous increase in the depth of coal mining, as well as gradual improvement in the mechanization and automation of digging technology. However, accidents and problems caused by mine dust have meanwhile become increasingly prominent. Especially, the high-concentration dust pollution in the staff working area at fully mechanized working face is a serious threat to coal mine safety production and occupational health. High-concentration dust is the primary source of explosion accident in coal mine [1,2]. Since 1949, there have been 25 serious accidents in coal mines in China, each with a death toll over 100. Among them, 13 accidents were caused by coal dust explosion or mixed dust deflagration, resulting in 2,274 deaths. In addition, for mine workers, high-concentration dust is the direct cause of pneumoconiosis [3]. According to the data released from Disease Prevention and Control Bureau, National Health and Family Planning Commission of PRC, there have been 853,662 reported cases of occupational diseases in China as of the end of 2014. Among them, 776,300 cases are pneumoconiosis, accounting for 90.94% of the total. Among all the working steps involved in fully mechanized working face, the step of coal cutting produces the largest amount of dust, which accounts for more than 90% of the total dust produced in a working cycle. The high-concentration dust spreads from the working face to other regions in the roadway driven by air flow, and results in dust of high concentration in the staff working area at fully mechanized working face.

At present, the dust pollution in fully mechanized working face is in general controlled by a local forced-exhaust overlap ventilation system. Researchers have proposed to form a dust-control air curtain to prevent dust diffusion, and to remove the dust-laden air by an exhaust ventilator [4–6]. In the recent two decades in China, air curtain dust control technology has been used in coal mine. Shi et al. [7] proposed the concept of air-curtain partition for dust isolation. They analyzed the installation angle of the

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http://dx.doi.org/10.1016/j.apt.2017.04.019

Please cite this article in press as: H. Wang et al., Effects of radial air flow quantity and location of an air curtain generator on dust pollution control at fully mechanized working face, Advanced Powder Technology (2017), http://dx.doi.org/10.1016/j.apt.2017.04.019

dust-control air curtain and optimized it for dust isolation. Wang et al. [8] designed an air curtain dust control system composed of a device which generates a lateral dust-proof air curtain. Nie et al. [9] developed a novel wall-attached ventilation duct, and analyzed its dust-control airflow field. These authors also established a closed-type dust control system for a fully mechanized working face and achieved a good effect. Cheng et al. [10] optimized the parameters for air curtain dust control system and verified the rationality of parameter setting by engineering application.

For a long period, studies about the forced-exhaust overlap ventilation system with an air curtain generator have been concentrated on the following aspects: (1) the formation mechanism of the swirling air curtain; (2) the improved design of the air curtain generator; (3) the evaluation of dust removal efficiency. However, the ventilation parameters of air curtain generator, including the radial air flow quantity and the distance of the air curtain generator from the working face, are determined largely based on experience which lacks accuracy and objectivity. This fact leads to difficulty in forming an effective dust-control air curtain and imposes strong restriction in dust pollution control.

Numerical simulation has played an irreplaceable role in studying the mechanisms of the airflow field migration for dust diffusion control. Nakayama et al. [11] simulated the airflow migration in the fully-mechanized working face and the simulation results of airflow velocity were close to the measured data. Aminossadati and Hooman [12], Parra et al. [13] and Torano et al. [14] used CFD technology to establish ventilation system models for coal mine roadway and validated them with experimental measurement in real roadway. Wang et al. [15] numerically simulated the dust concentration variation in a pressurized ventilation process using the CFD discrete phase model, and presented the distribution of dust concentration along the flow path. Torano et al. [16], Jiang et al. [17] analyzed the migration and diffusion of the airflow field and dust field of a working face under the forced-exhaust conditions, by coupling the numerical simulation with a field measurement. Nie et al. [18] analyzed the effect of ventilation conditions on the coal face's forced-exhaust overlap ventilation system using CFD-FLUENT software, and discovered a mathematical relationship between the dust diffusion distance and ventilation conditions.

Based on the previous research methods and results, this study focused on the 2–109$_2$ fully mechanized working face in Xinzhi coal mine (Huozhou Coal Electricity Group Co., Ltd., Shanxi, China), where a wall-attached ventilation duct was used as the air curtain generator. The airflow field migration and dust diffusion at various radial air flow quantities and various generator locations were simulated using FLUENT software. This study provides theoretical reference for field application of air curtain dust control technology.

2. Mathematical model and numerical solution

The fully mechanized working face has an air-particle two-phase flow field that is of high level of complexity. According to the characteristics of the dust-laden flow field, a $k-\varepsilon-\Theta-k_p$ mathematical model, which combines the Euler-Euler model and the Euler–Lagrange model [19,20,14,16], is developed to account for the dust spatial diffusion law at fully mechanized working face with an air curtain generator. The model is based on air-particle two-phase flow theory and characteristics [21,22]. The expression of the particle phase stress and the closed equation group to describe the particle flow are deduced. The governing equations of the air-particle two-phase turbulent flow are as follows.

Continuity equation of air phase:

$$\frac{\partial(\alpha\rho)_q}{\partial t}+\frac{\partial(\alpha\rho U_i)_q}{\partial x_i}=-\frac{\partial}{\partial x_i}\left[\overline{(\alpha\rho)'_q U'_{i,q}}\right] \tag{1}$$

where α is the volume fraction of air phase in the control volume; ρ is density, kg/m^3; the subscript q denotes the gas phase; U is the velocity vector, m/s; t is time, s; the subscript i is the tensor index, $i = 1, 2, 3$.

Quasi density continuous equation of particles:

$$\frac{\partial(\alpha\rho)_p}{\partial t}+\frac{\partial(\alpha\rho U_i)_p}{\partial x_i}=-\frac{\partial}{\partial x_i}\left[\overline{(\alpha\rho)'_p U'_{i,p}}\right] \tag{2}$$

Momentum equation of gas phase:

$$\begin{aligned}\frac{\partial(\alpha\rho U_j)_q}{\partial t}+\frac{\partial(\alpha\rho U_i U_j)_q}{\partial x_i}=&-\alpha_q\frac{\partial p}{\partial x_j}+\alpha_q\rho_q g_j+\frac{\partial\tau_{i,j}}{\partial x_i}+\beta_j(U_{j,p}-U_{j,q})\\&-\frac{\partial}{\partial x_i}\left(\alpha_q\rho_q\overline{U'_{i,q}U'_{j,p}}\right)\end{aligned} \tag{3}$$

$$\tau_{i,j}=\mu_q\left[\left(\frac{\partial U_{j,q}}{\partial x_i}+\frac{\partial U_{i,q}}{\partial x_j}\right)-\frac{2}{3}\delta_{i,j}\frac{\partial U_{k,q}}{\partial x_k}\right] \tag{4}$$

Momentum equation of particles:

$$\begin{aligned}\frac{\partial(\alpha\rho U_j)_p}{\partial t}+\frac{\partial(\alpha\rho U_i U_j)_p}{\partial x_i}=&-\alpha_p\frac{\partial p}{\partial x_j}+\rho_p g_j+\frac{\partial\Pi_{i,j}}{\partial x_i}+\beta_j(U_{j,q}-U_{j,p})\\&-\frac{\partial}{\partial x_i}\left(\alpha_p\rho_p\overline{U'_{j,p}U'_{i,p}}\right)\\&-\frac{\partial}{\partial x_i}\left[U_{j,p}\overline{(\alpha_p\rho_p)'U'_{i,p}}+U_{i,p}\overline{(\alpha_p\rho_p)'U'_{j,p}}\right]\end{aligned} \tag{5}$$

Equation of particle temperature Θ:

$$\begin{aligned}&\frac{3}{2}\left[\frac{\partial}{\partial t}(\alpha\rho\Theta)_p+\frac{\partial}{\partial x_i}(\alpha\rho U_i\Theta)_p\right]\\&\quad=\Pi_{i,j}\frac{\partial U_{j,p}}{\partial x_i}+\frac{\partial}{\partial x_i}\left(\Gamma_\Theta\frac{\partial\Theta}{\partial x_i}\right)-\gamma-\frac{3}{2}\alpha_p\rho_p\overline{U'_{i,p}\Theta}\\&\quad-\frac{3}{2}\frac{\partial}{\partial x_i}\left[\Theta\overline{(\alpha_p\rho_p)'U'_{i,p}}+U_{i,p}\overline{(\alpha_p\rho_p)'\Theta'}\right]\end{aligned} \tag{6}$$

In Eqs. (1)–(6), the subscript p denotes the particulate phase; the subscript j and k are the tensor indices; p is pressure, Pa; g is the gravitation acceleration, m/s^2; τ is the shear force between air phases, N; β is the inter-particle air drag coefficient; μ is shear viscosity; $\delta_{i,j}$ is "Kronecker Delta", when $i=j$, $\delta_{i,j}=1$, when $i\neq j$, $\delta_{i,j}=0$; Γ_Θ is the temperature transport coefficient of particles; γ is the collision energy dissipation, and can be expressed as [23]:

$$\gamma=3(1-e^2)\alpha_p^2\rho_p g_0\Theta\left[\frac{4}{d_p}\sqrt{\frac{\Theta}{\pi}}-\frac{\partial U_{k,p}}{\partial x_k}\right] \tag{7}$$

where e is the collision recovery coefficient of the particle. When $e = 1$, elastic collisions occur between particles and energy does not dissipate; when $e = 0$, fully inelastic collisions occur between particles; when $0 \leq e < 1$, the energy dissipates during inelastic collisions between particles. In addition,

$$g_0=\left[1-\left(\frac{\alpha_p}{\alpha_{p,\max}}\right)^{\frac{1}{3}}\right]^{-1} \tag{8}$$

$$\Pi_{i,j}=-p_p+\left(\xi_p-\frac{2}{3}\mu_p\right)\delta_{i,j}\frac{\partial U_{k,p}}{\partial x_k}\mu_p\left(\frac{\partial U_{j,p}}{\partial x_i}+\frac{\partial U_{j,p}}{\partial x_j}\right) \tag{9}$$

where ξ_p is the overall viscosity of particles.

Equation of the gas-phase turbulence energy k:

$$\frac{\partial}{\partial t}(\alpha_q\rho_q k)+\frac{\partial}{\partial x_j}(\alpha_q\rho_q U_{j,q}k)=\frac{\partial}{\partial x_j}\left(\frac{\mu_e}{\sigma_k}\frac{\partial k}{\partial x_j}\right)+G_k+G_p-\alpha_q\rho_q\varepsilon \tag{10}$$

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