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Modeling the influence of forced ventilation on the dispersion of droplets ejected from roadheader-mounted external sprayer

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ABSTRACT

In order to reveal the influence of forced ventilation on the dispersion of droplets ejected from roadheader-mounted external sprayer, the paper studies the air-flowing field and the droplet distribution under the condition of gentle breeze and normal forced ventilation in heading face using the particle tracking technology of computational fluid dynamics (CFD). The results show that air-flowing tendency in the same section presents great comparability in the period of gentle breeze and forced ventilation, and the difference mainly embodies in the different wind velocity. The influence of ventilation on the dispersion of droplets is faint under the gentle breeze condition. The droplet can be evenly distributed around the cutting head. However, under the normal forced ventilation, a large number of droplets will drift to the return air side. At the same time, droplet clusters are predominantly presented in the lower part of windward side and the middle of the leeward side around the cutting head. In contrast, the droplet concentration in other parts around cutting head decreases a lot and the droplets are unable to form close-grained mist curtain. So the dust escape channel is formed. In addition, the simulation results also reveal that the disturbance of air flow on the droplet distribution can be effectively relieved when using ventilation duct with Coanda effect (VDCE). Field experiment results show that the dust suppression efficiency of total dust and respirable dust increases respectively by 10.5% and 9.3% when using VDCE, which proves that it can weaken the influence of airflow on droplet dispersion.

1. Introduction

Dust is one of the main causes of disasters and occupational hazards in the mining process, which can lead to coal dust explosion and coal workers' pneumoconiosis (CWP), and cause heavy casualties and huge economic losses [1,2]. At present, water spraying is one of the key technologies for dust control. It is widely used in underground coal mines. But the dust suppression efficiency of water spraying is still low, and it is difficult to satisfy the user's requirements [3–5]. Due to the gas prevention requirements in gassy and outburst coal mine in China, the supply amount of air is large in heading face. However, the actual experiences enunciate that the dust removal efficiency of water spraying is significantly depressed in the heading face with large air supply. Except of the imperfect parameter design for spray equipment, the ventilation conditions are also the important reasons. So it is essential to study how ventilation conditions affect the spraying, which has important directive significance in further investigating the methods to improve dust removal efficiency in the heading face with large air supply. Nie et al. studied the disturbance of air flow on the spray of atomized particles. And the results show that the airflow causes an overall increase in droplet size [6]. Grundnig et al. analyzed the influence of air humidity on the suppression of fugitive dust by using a water spraying system in a confined space and found that the higher the relative humidity, the lower the needed water flux to reach equal dust suppression efficiency, and they also described a mathematical equation to calculate the dust suppression efficiency through water flux and relative humidity [7]. However, there is a few studies on the relationships between air flow and the dispersion of droplets in heading face. This problem will be discussed in this thesis.

Forced ventilation is common on the heading face in China because of its long effective range, excellent gas releasing and heat dissipation [8]. As for the internal sprayer mounted on the cutting head of roadheader, it has high failure probability and easy-affected atomization process. The external sprayer is relatively reliable, so it plays the dominant role in dust suppression practice, which is also the focus of this article. Therefore, it is necessary to explore how the forced ventilation influences water spraying and it is also the aim of this paper. The influence process is so complex that it is difficult to study by field experiment and laboratory experiment. As a result, the numerical simulation is the best choice.

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2. Numerical simulation method

2.1. Physical model

In order to simulate the dispersion of droplets ejected from roadheader-mounted external sprayer influenced by forced ventilation, a model is made with Gambit according to the actual size of working face. This model is based on the actual conditions of 22608 Auxiliary Roadway of Guandi Coal Mine, driven by Roadheader EBZ132. Forced ventilation runs in this working face with a counter rotary fan. The actual supplied airflow of this roadway (Q) is 260 m^3/min, and the air velocity of ventilation tubing exit (vf) is 5.5 m/s. The excavation roadway is 30 m long, and its cross section is 4.6 m wide and 3 m high. The main body of roadheader, located at a distance of 1.5 m from the face, measures 9 m (Length) × 2.8 m (Width) × 1.5 m (Height). The diameter and length of the cutting arm are 0.6 and 0.9 m respectively. The medial axis of the cutting arm is located 0.75 m to the ground. The ventilation tubing is located 5 m to the face, with a size of 1 m diameter, 25 m long and 0.2 m far to both roof and sidewall. Besides, this article has simplified the model for calculating as follows:

(1) Assume the section of excavation roadway as regular rectangle, excluding factors as the support's influence on the shape of section.
(2) Assume body of roadheader as regular cuboid, the cutting arms of roadheader and the ventilation tubing as regular cylinder, excluding other accessory equipment.

Based on conditions mentioned above, Tet/hybrid was used for mesh generation of the calculated area. Fig. 1 shows the mesh generation of physical model.

2.2. Mathematical model

Under the influence of ventilation, droplet movement field is the result of the interaction between the air and droplets. Due to its small percentage, the droplet is regarded as discrete phase and the air as continuous phase. The Lagrangian discrete phase model in Fluent follows the Euler–Lagrange approach. The fluid phase is treated as a continuum by solving the time-averaged Navier–Stokes equations, while the dispersed phase is solved by tracking a large number of particles through the calculated flow field. Particle tracking technique of DPM model is applied to the simulation of droplet migration [9–12].

(1) Mathematical model of continuous phase

Suppose gas phase flow in heading face as steady incompressible adiabatic flow, then the governing equations for gas phase flow can adopt three dimensional steady incompressible N–S equations, and the equation for turbulent flow can be RNG κ–ε.

Continuous equation is as follow:

$$\frac{\partial \rho \mu}{\partial x}+\frac{\partial \rho v}{\partial y}+\frac{\partial \rho w}{\partial z}=S_{\mathrm{m}} \tag{1}$$

where ρ is the fluid density; μ, v, w the velocity components on three axes for micro unit; and S_{m} the mass added to the continuous phase.

Momentum conservation equations are as follow:

$$\frac{\partial(\rho uu)}{\partial x}+\frac{\partial(\rho uv)}{\partial y}+\frac{\partial(\rho uw)}{\partial z}=\frac{\partial}{\partial x}\left(\mu_{\mathrm{eff}}\frac{\partial u}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu_{\mathrm{eff}}\frac{\partial u}{\partial y}\right)+\frac{\partial}{\partial z}\left(\mu_{\mathrm{eff}}\frac{\partial u}{\partial z}\right)-\frac{\partial p}{\partial x}+S_u \tag{2}$$

$$\frac{\partial(\rho vu)}{\partial x}+\frac{\partial(\rho vv)}{\partial y}+\frac{\partial(\rho vw)}{\partial z}=\frac{\partial}{\partial x}\left(\mu_{\mathrm{eff}}\frac{\partial v}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu_{\mathrm{eff}}\frac{\partial v}{\partial y}\right)+\frac{\partial}{\partial z}\left(\mu_{\mathrm{eff}}\frac{\partial v}{\partial z}\right)-\frac{\partial p}{\partial y}+S_v \tag{3}$$

$$\frac{\partial(\rho wu)}{\partial x}+\frac{\partial(\rho wv)}{\partial y}+\frac{\partial(\rho ww)}{\partial z}=\frac{\partial}{\partial x}\left(\mu_{\mathrm{eff}}\frac{\partial w}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu_{\mathrm{eff}}\frac{\partial w}{\partial y}\right)+\frac{\partial}{\partial z}\left(\mu_{\mathrm{eff}}\frac{\partial w}{\partial z}\right)-\frac{\partial p}{\partial z}+S_w \tag{4}$$

where p is the pressure on the fluid micro unit; μ_{eff} the coefficient of viscosity; μ the dynamic viscosity of the fluid; μ_t the turbulent viscosity; and S_u, S_v, S_w the general source items for kinetic energy conservation.

The double equations for RNG κ-ε model is as follow:

$$\frac{\partial(\rho ku)}{\partial x}+\frac{\partial(\rho kv)}{\partial y}+\frac{\partial(\rho kw)}{\partial z}=\frac{\partial}{\partial x}\left(\alpha_k u_{\mathrm{eff}}\frac{\partial k}{\partial x}\right)+\frac{\partial}{\partial y}\left(\alpha_k u_{\mathrm{eff}}\frac{\partial k}{\partial y}\right)+\frac{\partial}{\partial z}\left(\alpha_k u_{\mathrm{eff}}\frac{\partial k}{\partial z}\right)-\rho\varepsilon+G_k \tag{5}$$

$$\frac{\partial(\rho \varepsilon u)}{\partial x}+\frac{\partial(\rho \varepsilon v)}{\partial y}+\frac{\partial(\rho \varepsilon w)}{\partial z}=\frac{\partial}{\partial x}\left(\alpha_\varepsilon u_{\mathrm{eff}}\frac{\partial \varepsilon}{\partial x}\right)+\frac{\partial}{\partial y}\left(\alpha_\varepsilon u_{\mathrm{eff}}\frac{\partial \varepsilon}{\partial y}\right)+\frac{\partial}{\partial z}\left(\alpha_\varepsilon u_{\mathrm{eff}}\frac{\partial \varepsilon}{\partial z}\right)+\frac{\varepsilon}{k}(C_{1\varepsilon}G_k-C_{2\varepsilon}\rho\varepsilon) \tag{6}$$

where $C_{1\varepsilon}$ and $C_{2\varepsilon}$ are the empirical constants; α_κ and α_ε the equivalent Prandtl number for turbulence energy κ and dissipation rating ε.

(2) Mathematical model of dispersed phase

Fluent predicts the trajectory of a discrete phase particle by integrating the force balance on the particle, which is written in a Lagrangian reference frame. This force balance equates the particle inertia with the forces acting on the particle, and can be written as

$$\frac{\mathrm{d}u_p}{\mathrm{d}t}=F_D(u-u_p)+\frac{g_x(\rho_p-\rho)}{\rho_p}+F_x \tag{7}$$

where F_x is the additional acceleration (force/unit particle mass) term; and $F_D(u-u_p)$ the drag force per unit particle mass.

$$F_D=\frac{18\mu}{\rho_p d_p^2}\frac{C_D Re}{24} \tag{8}$$

where u is the gas phase velocity; u_p the droplet velocity; μ the molecular viscosity of the gas; ρ the gas density; ρ_p the density of the droplet; C_D the drag coefficient; and d_p the droplet diameter. Re is the relative Reynolds number, which is defined as

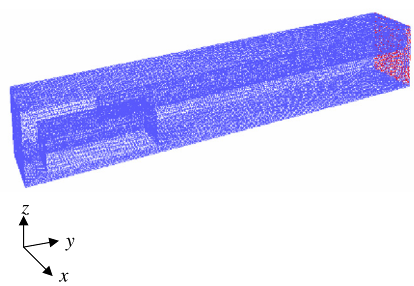

Fig. 1. Mesh generation of physical model.