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Numerical simulation of CO distribution discharged by flame-proof vehicle in underground tunnel of coal mine

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ABSTRACT

CO discharged by mine flame-proof vehicles can result in wrong signals to the early-warning system of spontaneous combustion often occurred in coal mines as CO is one of the index gases when forecasting and early warning coal spontaneous combustion in underground mine. Traditional method is to install sensors in the air intake system to monitor the CO concentration. In the present paper, a number of CO distribution simulations are performed using commercial FLUENT software. When a mine flame-proof vehicle running at a speed of 7 m s^{-1} in an underground tunnel while the inlet velocity of roadway is 3 m s^{-1}, dynamic distribution of CO concentration discharged by mine flame-proof vehicle within $t = 1-5$ s is obtained, and variation of CO concentration on static monitoring points is obtained at the same time while simulating. The simulation results indicate that: the region of CO concentration greater than 0.0024% was in the scope from vehicle tailgate to the back which is irregular shapes, and it reduces to less than 0.0024% in short time, about 1 s. In front of the vehicle CO concentration is always a fixed value or even lower than 0.0019%. For comparative analysis, 4 monitoring points are arranged to monitor the CO concentration in actual underground roadway. And the actual measured data verified the correctness of numerical simulation data.

1. Introduction

In the process of coal spontaneous combustion, with different degrees oxidation of coal, a variety of gases generate during coal–oxygen reaction. The emergence and emission of these gases basically reflect the degree of coal spontaneous combustion (Torano et al., 2009). In the early prediction of coal spontaneous combustion, index gas analysis has played an important role (Li et al., 2006). As one of the major index gases and an important part of coal spontaneous combustion research in gob (Xiao et al., 2007; Sahu et al., 2010; Sensogut and Ozdeniz, 2005), CO appears slowly at a lower temperature and has two advantages: be detected easily and measured accurately. In a long term, Chinese and foreign scholars have taken a lot of experiments on CO generated by coal spontaneous combustion (Chen, 1999; He et al., 2003; Li et al., 2004). Regulars of coal spontaneous combustion generating CO in gob underground have been analyzed and summarized, which provides theoretical foundation for controlling coal spontaneous combustion and CO emission. But single emergence of CO cannot be determined if coal spontaneous combustion in mine has occurred. When a mine flame-proof vehicle is used in underground tunnel, toxic gas, CO and NO_2 are released. It interferes the CO prediction on coal spontaneous combustion in gob someway. This hazardous greenhouse gas has been recognized as one of the prime causes of underground mine disasters around the world. Several fatalities in underground coal mine that are related to the presence of CO has been reported (Torano et al., 2009; Lu et al., 2004). Traditional measurement employed sensors in the air intake system to monitor the CO concentration generated by mine flame-proof vehicle and to understand the CO spread in underground roadways, this may consume a large amount of energy and resources (Zhao, 2008). In tandem with experimental design and studies, numerical modeling has come to play an important role in designing and examining mine ventilation system in underground mine (Reddy, 2009).

The aim of this paper is to prove that the mentioned FLUENT allows to use and obtain in a continuous way how airflow and CO spread along the roadway in underground coal mine and to analyze their influence on the prediction of CO generated by coal spontaneous combustion in gob.

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2. Mine flame-proof vehicle synopsis

There are varieties of mine flame-proof vehicles in China. In this paper, "WC20R(B)trackless diesel flame-proof rubber-tyred vehicle" is used for collecting and detecting the exhaust gas CO. This type of mine flame-proof vehicle is made in Shanxi Coal Equipment Co.,Ltd, Coal Research Institute. This vehicle belongs to the whole frame metal enclosed bus (Fig. 1). The emission target of the vehicle is CO $\leq$ 0.1%. By measuring the circumference of the exhaust duct, the diameter of the duct was 40 mm. Airflow velocity of 8.5–10 m s^{-1} was measured using a hand-held anemometer. Some air-tight bags were used to collect the exhaust gas from the duct, and then the gases were detected by gas chromatography instrument in laboratory. The CO concentration of the exhaust gas from mine flame-proof vehicle duct was identified as 0.0365% (365 ppm).

As the ambient temperature was 25 °C and the surrounding pressure was standard atmospheric pressure (101.325 kPa) when testing, the following formula could be applied to calculate CO emission mass of per unit volume exhaust gas.

$$C = \frac{C' \cdot M}{22.4} \cdot \frac{273}{273 + T} \tag{1}$$

In Eq. (1), C is gas mass of per unit volume, mg m^{-3}; C' is gas concentration represented by ppm; M is molecular of gas; *22.4* is air average molar volume at standard conditions (0 °C, 101.325 kPa), L mol^{-1}; T is ambient temperature, °C. In this paper, C' is detected as 365 ppm, M is 28 (which is molecular of CO), and T is 25 °C. It can be calculated that CO concentration at the duct of mine flame-proof vehicle is 0.418 g m^{-3}. When the airflow velocity of the exhaust port is 9.25 m s^{-1} (this value of velocity is the mathematical mean of minimum value 8.25 m s^{-1} and maximum value 10 m s^{-1}). The CO mass flow rate of exhaust gas emitted from the mine flame-proof vehicle is $5.3551e^{-3}$ g s^{-1} through calculating. This will be the CO source item in FLUENT simulation.

3. Numerical simulation

3.1. Governing equations

CO diffusion in underground roadway obeys fluid flow physical conservation law including three basic conservations (mass, energy and momentum). When flowing in underground tunnel, CO is mixed and interacts with air, that's why CO diffusion also abides the conservation of components (Kurnia et al., 2014). Airflow in underground tunnel is in a state of turbulent, and the fluid flow can be considered incompressible and unsteady.

Fig. 1. WC20R(B)trackless diesel flame-proof vehicle.

Mass conservation equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho V = 0 \tag{2}$$

Momentum equation:

$$\frac{\partial(\rho V)}{\partial t} + \nabla \bullet (\rho VV) = -\nabla p + \nabla \bullet (\tau) + \rho g \tag{3}$$

Energy conservation equation:

$$\frac{\partial(\rho E)}{\partial t} + \nabla \bullet (V(\rho E + p)) = \nabla \bullet \left(k_{eff} \nabla T - \sum_j h_j J_j + \left(\tau_{eff} \bullet V \right) \right) \tag{4}$$

Species transport equation:

$$\frac{\partial(\rho C_j)}{\partial t} + div(\rho V C_j) = div(R_j grad(\rho C_j)) \tag{5}$$

where ρ is the fluid density, kg m^{-3}; t is time, s; V is the fluid velocity, m s^{-1}; p is pressure, Pa; τ is the viscous stress tensor, N m^{-2}; g is gravity acceleration, m s^{-2}; T is temperature, K; E is total energy including internal energy and kinetic energy, J; k_{eff} is the effective fluid thermal conductivity; h_j, J_j are enthalpy and diffusion flux of component j respectively; C_j is volume concentration of component j; R_j is diffusion coefficient of component j, m^2 s.

The turbulence model is the key component in representing flow behavior in underground roadway (Chen et al., 2013). In 2006, Parra et al. (Versteeg and Malalasekera, 1995) have conducted a comparison of flow behavior from turbulence models such as Spalart-Allmaras, k-epsilon, k-omega and Reynolds Stress Model(RSM). k-epsilon model widely used in engineering field is chosen as it gives reasonable good prediction between simulation results and experimental data. In short, k-epsilon model considers two-equation model which solves for turbulent kinetic energy, k, and its rate of dissipationε, which is coupled with turbulent viscosity. This model is given as:

$$\frac{\partial(\rho k)}{\partial t} + \nabla \bullet (\rho V k) = \nabla \left(\left(\mu + \frac{\mu_t}{\sigma_k} \right) \nabla k \right) + G_k - \rho\varepsilon \tag{6}$$

$$\frac{\partial(\rho \varepsilon)}{\partial t} + \nabla \bullet (\rho V \varepsilon) = \nabla \left(\left(\mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \nabla \varepsilon \right) + C_{1\varepsilon} \frac{\varepsilon G_k}{k} + C_{2\varepsilon} \rho \frac{\varepsilon^2}{k} \tag{7}$$

where G_k is the generation of turbulence kinetic energy due to mean velocity gradients; $C_{1\varepsilon}$, $C_{2\varepsilon}$ are constants,1.44 and 1.92 respectively; σ_k, σ_ε are respectively turbulent Prandtl numbers for k and ε; μ_t is turbulent viscosity expressed as:

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \tag{8}$$

The values of C_μ, σ_k and σ_ε are 0.09, 1 and 1.3, respectively.

3.2. Geometric models

A two-dimensional model is developed for a typical Xingtao mine roadway region where the mine frame-proof vehicle works, as shown in Fig. 2. Details on the geometrical parameters are: $L_{\text{tunnel}} = 50$ m; $W_{\text{tunnel}} = 4$ m; $L_{\text{vehicle}} = 5$ m; $W_{\text{vehicle}} = 2$ m; the