International Journal of Mining Science and Technology 27 (2017) 657–662

Contents lists available at ScienceDirect

International Journal of Mining Science and Technology

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

# Prediction of air flow, methane, and coal dust dispersion in a room and pillar mining face

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ARTICLE INFO

*Article history:*
Received 1 December 2016
Received in revised form 18 January 2017
Accepted 10 March 2017
Available online 18 May 2017

*Keywords:*
Dust
Methane
Mine ventilation
Mining machine

ABSTRACT

In underground coal mines, uncontrolled accumulation of methane and fine coal dust often leads to serious incidents such as explosion. Therefore, methane and dust dispersion in underground mines is closely monitored and strictly regulated. Accordingly, significant efforts have been devoted to study methane and dust dispersion in underground mines. In this study, methane emission and dust concentration are numerically investigated using a computational fluid dynamics (CFD) approach. Various possible scenarios of underground mine configurations are evaluated. The results indicate that the presence of continuous miner adversely affects the air flow and leads to increased methane and dust concentrations. Nevertheless, it is found that such negative effect can be minimized or even neutralized by operating the scrubber fan in suction mode. In addition, it was found that the combination of scrubber fan in suction mode and brattice results in the best performance in terms of methane and dust removal from the mining face.

## 1. Introduction

Coal mining is considered as one of the world's most challenging operations. There are many hazards associated with coal mining such as explosion, structural collapse, hazardous gasses and particulates, moving vehicle and lack of respirable air. Of these hazards, the most severe is explosion. Firedamp explosions, majorly caused by methane, can trigger the more dangerous coal dust explosion which can cause fatalities. Even in developed countries, coal related fatalities are considerably high. For example, more than hundred thousand coal mine explosion fatalities have been recorded in the U.S [1]. The situation is more alarming in developing countries, as indicated by the increase of the occurrences and casualties in China [2]. This situation has prompted the mining community worldwide to explore and evaluate solutions to reduce and eliminate the hazards causing explosions. A large number of studies have been conducted and reported and the majority of research has been focused on mine ventilation as it directly affects the hazardous methane and dust accumulation in the mining face.

Pioneer studies on mine ventilation were directed at the fundamental aspects of mine ventilation. Kaliev and Akimbekov developed air motion model based on Bernoulli equation and Runge-Kutta method [3]. The results revealed that theoretical and experimental air flow rates differ by less than 10%. Riley and Edwards experimented the methane drainage system in mining [4]. It was found that methane drainage system has better efficiencies in advance mining compared to retreat mining. Subsequently, computational fluid dynamics (CFD) became widely utilized in mine ventilation studies due to its capability to predict methane dispersion. Some examples are studies conducted by Srinivasa et al., Uchino and Inoue and Tomate et al. [5–7].

Recently, research has been directed to explore ventilation methods and designs. This is mainly attributed to the fact that fundamentals have been established and significant advancement in computational power allows CFD simulations to be run at significantly reduced cost. Parra et al. examined ventilation near mining face and found that blowing ventilation, in terms of dust control, offers better dust dispersion than exhaust ventilation if the setback distance is 6 m or more [8]. Wu et al. studied three-dimensional gas transfer in coal mining and discovered that gas concentration along the intake side is lower compared to the return airway side [9]. Later, Torano et al. justified that simulations are consistent with experimental data and it also demonstrates that CFD is necessary to analyze ventilation systems [10]. Rodriguez and Lombardia found that different stone types result in different methane emissions [11]. Sasmito et al. examined four different turbulence models: Spallart-Almaras, k-epsilon, k-omega and Reynolds Stress

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http://dx.doi.org/10.1016/j.ijmst.2017.05.019
2095-2686/© 2017 Published by Elsevier B.V. on behalf of China University of Mining & Technology.

Model (RSM) [12]. It was found that "Spallart-Almaras" model, which consumes the least computational power, would be sufficient to predict flow behavior. Another finding is that in a typical room and pillar mining, flow stopping design can largely affect methane concentration. It is also found that "brattice-exhausting system" leads to the lowest methane concentration. Kurnia et al. numerically examined the relation between methane sources and methane dispersion as well as methane distribution within the mining tunnel [13]. Later, Kurnia et al. investigated intermittent ventilation system and discovered possible electricity saving plan [14]. Zhou et al. simulated scenarios with the existence of continuous miner [15]. The important findings from their study are (1) only very limited airflow could reach the mining face compared to total airflow, (2) methane release efficiency is not considerably affected by different source locations, however it is strongly influenced by the amount of methane released.

Dust concentration is another attractive research topic. Respirable dust inhale could adversely affect worker's health. Moreover, high dust concentration can trigger dust explosion and would be a disaster to the mine. Water spray system has been widely used for dust suppression due to its simplicity and effectiveness. As early as 1988, Aziz et al. already discovered that and thus, water is used to reduce dust content [16]. Recent results show that water can reduce dust concentration by up to 60% [17]. Torano et al. extended their own research from methane only to dust and developed a CFD model to match with field data [18]. Wei et al. simulated different scenarios of different exhausting pipe locations and diameters to reduce dust concentrations [19]. Dong et al. tested methane-air explosion mechanism with the existence of coal dust and obstacles in a pipe but lacking theory to explain the result [20]. Zhou et al. investigated dust diffusion in a specific forced-exhausted hybrid tunnel wit continuous miner [21]. Wang et al. also did similar dust investigation in a forced-exhausted hybrid tunnel for a rectangular-shaped laneway [22]. Kurnia et al. investigated different ventilation tools on dust removal and energy saving perspectives and found brattice, generally, have the best dust removing efficiency at a cost of more energy consumption [13]. Kurnia et al. investigated brattice setup and dust control in a typical mine tunnel [23]. Hu et al. simulated respirable dust characteristics in another typical mine tunnel [24].

Many studies have investigated methane and dust concentrations separately. However, none of them focused on the existence of both methane and dust although they are both critical pollutants to coal mines. This study investigates the flow behavior, as well as the methane and dust dispersion characteristics in the mining face of an underground coal mine. Moreover, continuous miner and, also ventilation tools are included in the study since the mining machine takes up a very large area inside an active mining face, which is likely to cause flow changes (compared to scenarios without continuous miner) and possibly dead zones for both methane and dust.

## 2. Model formulation

A three-dimensional model is developed to imitate the mining region, as shown in Fig. 1. Ventilation air is supplied from inlet at a speed of 2 m/s. At the active mining face, methane will be leaking into the tunnel at a speed of 0.002874 m/s and dust is generated by continuous miner at a speed of 1 m/s with flow rate of 0.0062 kg/s. Detailed properties are summarized in Table 1.

### 2.1. Governing equations

The steady conservation equations for mass, momentum, energy and species are as follows [22]:

$$\nabla \cdot \rho \mathbf{U} = 0 \tag{1}$$

$$\nabla \cdot \rho \mathbf{U}\mathbf{U} = -\nabla p + \nabla \tau + \rho \mathbf{g}, -\mathbf{F}_{dust} \tag{2}$$

$$\nabla \cdot (\rho c_p \mathbf{U} T) = \nabla \cdot \left( k_{eff} + \frac{c_p \mu_t}{\mathrm{Pr}_t} \right) \nabla T \tag{3}$$

$$\nabla \cdot (\rho \omega_i \mathbf{U}) = \nabla \cdot \left( \rho D_{i,eff} + \frac{\mu_t}{Sc_t} \right) \nabla \omega_i \tag{4}$$

where $\rho$ is the fluid density; $U$ the fluid velocity; $p$ the pressure; $\mu$ the dynamic viscosity of the fluid; $g$ the gravity acceleration; $c_p$ the specific heat of fluid; $k_{eff}$ the thermal conductivity of the fluid; $\mu_t$ the turbulence viscosity; $T$ the temperature number; $\omega_i$ the mass fraction of species $i$ (i.e. $O_2$, $CH_4$ and $N_2$); $D_{i,eff}$ the diffusivity of species $i$; and $Pr_t$ and $Sc_t$ the turbulence Prandtl and Schmidt number. The fluid stress tensor of fluid is given by:

$$\tau = (\mu + \mu_t)\left( \nabla \mathbf{U} + (\nabla \mathbf{U})^T \right) - \frac{2}{3}\left[ (\mu + \mu_t)(\nabla \cdot \mathbf{U})\mathbf{I} + \rho k \mathbf{I} \right] \tag{5}$$

where $\mu$ is the fluid dynamic viscosity; and $I$ the second order unit tensor.

Oxygen, water vapor, nitrogen and methane formed the air mixture in the underground tunnel. The interactions between the species are captured in the mixture density which follows incompressible ideal gas law

$$\rho = \frac{pM}{RT} \tag{6}$$

where $R$ is the universal gas constant; and $M$ the mixture molecular weight given by

$$M = \left[ \frac{\omega_{CH_4}}{M_{CH_4}} + \frac{\omega_{O_2}}{M_{O_2}} + \frac{\omega_{H_2O}}{M_{H_2O}} + \frac{\omega_{N_2}}{M_{N_2}} \right]^{-1} \tag{7}$$

Here, $M_i$ is the molecular mass of species $i$. Mass fraction of the 4 species, that is, $CH_4$, $O_2$, $H_2O$ and $N_2$, are in the following relations

$$\omega_{N_2} = 1 - (\omega_{O_2} + \omega_{H_2O} + \omega_{CH_4}) \tag{8}$$

The fluid mixture viscosity is calculated using

$$\mu = \sum_i \frac{x_i \mu_i}{\sum_j x_i \Phi_{i,j}} \quad \text{with} \quad i \quad \text{and} \quad j = \mathrm{CH_4, O_2, H_2O} \text{ and } \mathrm{N_2} \tag{9}$$

where $x_i$ is the mole fraction of species $i$ and $\Phi_{i,j}$ given in the following equation.

$$\Phi_{i,j} = \frac{1}{\sqrt{8}} \left( 1 + \frac{M_i}{M_j} \right)^{\frac{1}{2}} \left[ 1 + \left( \frac{\mu_i}{\mu_j} \right)^{\frac{1}{2}} \left( \frac{M_i}{M_j} \right)^{\frac{1}{4}} \right]^2 \tag{10}$$

The mole fractions are related to the mass fractions by

$$x_i = \frac{\omega_i M}{M_i} \tag{11}$$

Dust is generated at the mining face during excavation by the continuous miner and is dispersed by ventilation airflow. The dust movement is tracked by solving a differential equation for a discrete second phase in the Lagrangian reference frame. For first approximation, the particle collision is assumed to collide without creating bigger particle and no agglomeration. The force balance equates the dust particle inertia with the forces acting on the dust particle, shown as

$$\frac{d\mathbf{u}_{\text{dust}}}{dt} = \mathbf{F}_{\text{D}}(\mathbf{U} - \mathbf{u}_{\text{dust}}) + \frac{\mathbf{g}(\rho_{\text{dust}} - \rho)}{\rho_{\text{dust}}} \tag{12}$$

where $\rho_{\text{dust}}$ is the dust density, and $\boldsymbol{F}_D(\boldsymbol{U}\text{-}\boldsymbol{u}_{\text{dust}})$ the drag force per unit dust particle mass.