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Simulation of a novel intermittent ventilation system for underground mines

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A B S T R A C T

With increase of energy costs and implementation of carbon tax in many countries, a cost-effective mine ventilation system has become highly desirable in underground mine operations. In this study, a novel intermittent airflow ventilation system is proposed and evaluated via simulation with the goal of reducing the energy cost whilst maintaining methane level in the mining face below the allowable level. Parametric studies are conducted to investigate the effects of various factors influencing the effectiveness and performance of this novel intermittent ventilation system, in particular the effect of intermittency period, air velocity, and application of multiple outlet nozzles with intermittent on-off flapper valves for air flow control. Significant energy savings and air handling requirements are shown to be possible through the scheme proposed.

1. Introduction

During underground mining operation (especially underground coal mine), large amounts of methane are released in the face area. This hazardous greenhouse gas has for decades been recognized as one of the prime causes of underground mine disasters around the globe. Several major incidents and accidents related to the presence of methane in underground coal mines with fatalities have been reported (Torano et al., 2009). To eliminate such incidents and accidents, a good ventilation system is mandatory. According to US regulations, methane concentration should be maintained below 3% v/v while in other countries an even lower methane concentration is mandatory: 1% in Germany, 1.25% in UK, 2% in France and 2.5% in Spain (Noack, 1998). It is expected that these requirements will become increasingly stringent in future.

Most ventilation systems installed in underground coal mines nowadays supply excess fresh air to ensure safe methane concentration as required by local codes. A study by Reddy (2009) reveals that up to 60% of the total mining operating cost is attributable to mine ventilation cost, highlighting the huge amount of electrical energy consumed to drive fresh air to various locations in underground mine. With increase of energy costs and implementation of carbon tax in many countries, a cost-effective mine ventilation system which ensure a safe and productive environment in an underground mine whilst keeping energy usage and operating cost at minimum has become highly desirable for the mining industry. As such, a concept of ventilation-on-demand has received considerable attention (Tuck et al., 2006; Allen and Keen, 2008; O'Connor, 2008). The idea behind this concept is straightforward: supply adequate fresh air to a certain location only when it is needed. Application of this system in underground mine, however, will require complex control system and sophisticated monitoring devices and sensors.

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. Modeling allows innovation at very low cost. Among the first researchers conducting computational fluid dynamics (CFD) modeling to investigate ventilation airflow, methane emission and dust dispersion in underground mine were Heerden and Sullivan (1993). They examined ventilation airflow patterns around continuous miner in an active mining area and its effect on the methane and dust distribution. Next study was conducted by Srinivasa et al (1993). By utilizing commercially available CFD tools, they investigate flow behavior and dust movement in a longwall face. First validated CFD model on underground mine ventilation was developed by

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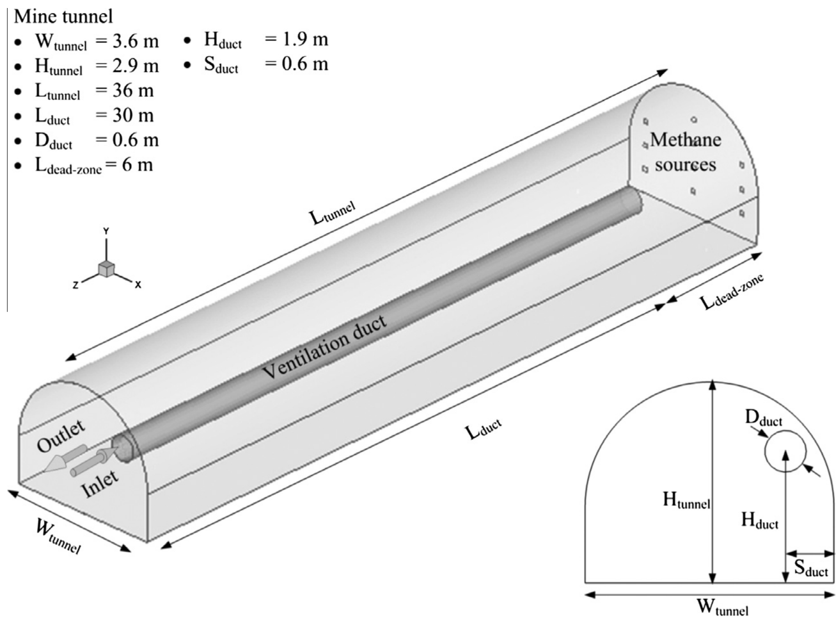

Fig. 1. Shcematic of an underground mine tunnel with ventilation duct.

Uchino and Inoue (1997) by using experimental data from both full-scale heading and a scale model. This model was extended to study methane distribution by Tomata et al (1999). Nakayama et al (1999) conducted similar studies by investigating methane gas distribution in a mining face by utilizing CFD software LASAR95/98. Their model prediction achieved relatively good agreement with the experimentally measured counterparts. Wala et al (2003, 2007) developed a CFD model for longwall as well as room and pilar mines and validated their model with the experimental data obtained from a lab-scale set-up. They extend their study by including the effect of scrubber operation on the face ventilation (Wala et al., 2008).

A multiphase Eularian model to predict dust behavior in a complex mine geometry was developed by Canoo (2004). Another computational study was conducted by Parra et al (2006). After validating their model, they investigated two scenario of additional ventilation system in a cul-de-sac mine: blowing and exhausting. Hargreaves and Lowndes (2007) numerically investigated the effect of the drivage of continuous miner on the flow behavior in underground mining face. Zheng and Tien (2008) conducted CFD modeling of diesel particulate matters dispersion in a mining face and examine the performance of blowing and exhausting ventilation system in reducing DPM concentration in the mining face. Torano et al (2009, 2011) conducted numerical study to evaluate methane and dust behavior in mining area and validate it with experimental data obtained from an underground mine in Spain. Recently, Sasmito et al (2013) reported a numerical study examining various auxiliary ventilation equipment's to provide better ventilation whilst keeping low energy usage.

In this study, a novel and original intermittent airflow ventilation system is proposed and evaluated via simulation with the goal of reducing the energy cost whilst maintaining methane level in the mining face below the allowable level. A computational fluid dynamic (CFD) approach is utilized to investigate the flow behavior and methane dispersion on mine tunnels with an intermittent flow ventilation system. In our physical model, methane is uniformly released from ten sources ($10 \times 10\ \mathrm{cm}^2$) in the mining face with total flow rate of $0.05\ \mathrm{m}^3\ \mathrm{s}^{-1}$. Parametric studies are conducted to investigate effects of various factors influencing the effectiveness and performance of this novel intermittent ventilation system: intermittency period, air velocity, and application of multiple outlet nozzles with intermittent on-off flapper valves for air flow control. It is noted that current mining codes refer only to steady flows. So, if the proposed scheme were to be applied, changes may be needed to local mining codes.

2. Mathematical formulation

A three-dimensional underground coal mining model is developed for a typical mine tunnel which is the simplest and most used in underground coal mining these days (please refer to Fig. 1). The mine tunnel 36 m long 3.6 m wide and 2.9 m high. A ventilation duct with a diameter of 0.6 m is hung at 1.9 m height from the floor and 0.6 m from the tunnel wall on the access road. Its setback distance from the mining face is 6 m.

2.1. Governing equations

In the tunnel flow, simultaneous mass, momentum, energy and species transport occur. Methane is released from specified discrete sources in the mining face and it is dispersed by the ventilation airflow. Conservation equations for mass, momentum, and species can be expressed as

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \mathbf{U} = 0, \tag{1}$$

$$\frac{\partial}{\partial t}(\rho \mathbf{U}) + \nabla \cdot \rho \mathbf{U}\mathbf{U} = -\nabla p + \nabla \cdot \boldsymbol{\tau} + \rho \mathbf{g}, \tag{2}$$

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

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

where ρ is the fluid density, $\mathbf{U}$ is the fluid velocity, p is pressure, $\boldsymbol{\tau}$ is the viscous stress tensor, $\mathbf{g}$ is gravity acceleration, c_p is the specific heat of the fluid, k_{eff} is the effective fluid thermal conductivity, T is the temperature, ω_i is the mass fraction of species i (O_2, CH_4 and N_2), $D_{i,eff}$ is the effective diffusivity of species i, μ_t is turbulent viscosity and Sc_t is the turbulent Schmidt number and Pr_t is the turbulent Prandtl number.