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Introduction and evaluation of a novel hybrid brattice for improved dust control in underground mining faces: A computational study

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ABSTRACT

A proper control and management of dust dispersion is essential to ensure safe and productive underground working environment. Brattice installation to direct the flow from main shaft to the mining face was found to be the most effective method to disperse dust particle away from the mining face. However, it limits the movement and disturbs the flexibility of the mining fleets and operators at the tunnel. This study proposes a hybrid brattice system - a combination of a physical brattice together with suitable and flexible directed and located air curtains - to mitigate dust dispersion from the mining face and reduce dust concentration to a safe level for the working operators. A validated three-dimensional computational fluid dynamic model utilizing Eulerian–Lagrangian approach is employed to track the dispersion of dust particle. Several possible hybrid brattice scenarios are evaluated with the objective to improve dust management in underground mine. The results suggest that implementation of hybrid brattice is beneficial for the mining operation: up to three times lower dust concentration is achieved as compared to that of the physical brattice without air curtain.

1. Introduction

In underground mines, proper dust control is vital to ensure safe and productive working environment. Typically, the presence of fine dust in the mining face due to mineral excavation causes serious health hazard to the miners. The fine dust particles are easily inhaled by miners and get deposited in the lungs which results in pneumoconiosis (CWP/black lung disease) and silicosis in the long term exposure [1,2]. In addition, the larger dust particle can disturb operators during operation and may cause injuries which adversely affect miners' productivity over time. Furthermore, in underground coal mines, the presence of coal dust can trigger explosion when it mixes with oxygen and spark. Numerous coal-dust and methane related incidents and accidents with fatalities have received significant attention all over the world [3]. There is thus a need to develop proper dust control system and management to ensure safe and productive underground working environment.

To date, various dust control strategies have been tested and applied in underground mines; among them, water spray has been widely used in underground mines due to its simplicity. With a good nozzle spray design, the water spray system can reduce dust concentration in the air of up to 60% [4]. Despite its advantages on reducing dust concentration, water spray possesses several drawbacks [5–7] as follows:

- Water quantity and quality is difficult to maintain as some of the water evaporates throughout the process resulting in unsustainable water cycle. Excessive amount of evaporation increases ambient relative humidity which, in turn, results in uncomfortable ambient environment. The water quality related to cleanliness cannot be guaranteed as it mixes with many impurities; thus, water treatment is sometime required which adds complexity and cost. Otherwise, it may block and clog the nozzle spray.
- Excessive water spray results in lower materials quality, for example, wet coal with high moisture content due to water spray has lower quality than dry coal; thus, additional coal drying process may be needed to improve the quality. In addition, wet materials typically have higher density (heavier) and it may change the characteristics of the materials (in the form of slurry instead of ore). This leads to difficulties in materials handling and transportation.
- Large amount of water is required for the spray system which needs to be pumped from the surface if the groundwater is not available and/or sufficient. This adds complexity and cost to the mining operation.

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- Once dust is airborne, additional dust control must be applied to dilute it, direct it away from the miners, or remove it from the working environment.

Other popular dust control strategies are water infusion, mix of water/wetting agent spray or foam spray, and ventilation [8–10]. These strategies, however, have limitations as well. For instance, water infusion and foam spray require complex equipment and large amount of water which adds complexity to the mine operation, similar to water spray. For the ventilation strategy, it typically requires large volume of fresh air to dilute the dust [9,10]; thus, proper ventilation design is necessary to effectively control the dust while minimizing complexity of the design and energy requirement. Ren et al. [11] employed computational fluid dynamic (CFD) model to predict respirable dust behavior in the mine intake roadway. They proposed two possible ways to mitigate dust: by modifying ventilation system and water spray to suppress and capture dust particles. Han et al. [12] simulated the dust suppression mechanism utilizing CFD software; they showed that suppression efficiency can be improved by up to 10% when using ventilation duct with Coanda effect (VDCE). Wang et al. [13] numerically evaluated the application of air curtain installed in the longwall mining shearer to isolate dust from the shearer operators. They showed that air curtain can effectively protect operators from dust exposure. Previous work in our group [14] showed that brattice ventilation is able to provide best dust management in the room and pillar mining as compared to blowing and/or suction ventilation configurations effectively with no additional power source required to drive fans and simpler design which make it suitable for application in underground mine. One of the major drawbacks in this design, however, is that the brattice installation limits the movement and flexibility of the operators and mining fleets to excavate materials and materials' handling transportation; to some extent, it reduces available space that is typically limited in small mines. It is therefore of interest to improve existing brattice ventilation design in order to accommodate the need of movement flexibility of miners and mining fleets for mineral extractions at the working environment.

To extend the work on the dust control and mitigation in underground mines, the aim of the work presented is threefold: (i) to evaluate the effectiveness of brattice blocking configuration; (ii) to propose implementation of hybrid brattice - a combination of a physical brattice along with suitably directed and located air curtains - and evaluate its possible configurations; and (iii) to investigate the effect of setback distance of the hybrid brattice to the mining face with respect to the dust concentration.

The layout of the paper is as follows. First the mathematical model is introduced. It solves for three-dimensional turbulence gas–solid flow, for which the gas phase is solved in Eulerian domain, comprising conservation equations of turbulent mass and momentum, whereas the solid particles phase is treated in Lagrangian approach. Two way coupling between particles tracking and continuum equations was adopted. The most commonly used K-Epsilon turbulent model is selected based on validation study performed in previous work [15,16]. The model is then solved using one-domain finite volume approach. Four different brattice blocking scenarios are examined with regard to the dust dispersion and management. Implementation of hybrid brattice is then introduced and three different air curtain configurations on the hybrid brattice are evaluated. We further examine the effect of setback distance of the hybrid brattice to the dust concentration. Finally, conclusions are drawn and extension of the works is highlighted.

2. Model development

A typical active mine development region in room and pillar mining is simulated using three dimensional computational fluid dynamic model as shown in Fig. 1. Ventilation air is supplied from the inlet and is directed to the mining face by brattice. At the active mining face, dust is generated during mechanical mining process and is assumed to flow at speed 1 m/s with total flow rate of 0.0062 kg/s [9]. Coal-high value dust is selected in this study as a typical dust found in underground coal mines. Detailed properties of the dust together with geometrical and operating parameters are summarized in Table 1.

2.1. Governing equations

The mathematical model for the continuum gas phase comprises conservation equations of turbulent mass and momentum.

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

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

where ρ is the fluid density, U is the fluid velocity, p is the pressure, μ is the dynamic viscosity of the fluid, I is the identity or second order unit tensor, g is the gravity acceleration and F_{dust} is the momentum transfer from the discrete phase (dust) to the continuous phase (air) which represents two-way gas–solid phase coupling.

2.2. Turbulence model

The most commonly used turbulence model in engineering, standard $k-\varepsilon$, is selected in this work based on validation with experimental flow measurement in our previous work [14–16]; for the sake of brevity, the validation is not repeated here. This model comprises two-equations that solve for turbulent kinetic energy, k, and its rate of dissipation, ε, and is coupled to the turbulent viscosity.

$$\frac{\partial}{\partial t}(\rho k) + \nabla \cdot (\rho \mathbf{u} k) = \nabla \cdot \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \nabla k \right] + G_k - \rho \varepsilon \tag{3}$$

$$\frac{\partial}{\partial t}(\rho \varepsilon) + \nabla \cdot (\rho \mathbf{u} \varepsilon) = \nabla \cdot \left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \nabla \varepsilon \right] + C_{1\varepsilon} \frac{\varepsilon G_k}{k} - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k} \tag{4}$$

In above equations, G_k represents the generation of turbulence kinetic energy due to the mean velocity gradients, $C_{1\varepsilon}$ and $C_{2\varepsilon}$ are constants, σ_k and σ_ε are the turbulent Prandtl numbers for k and ε, respectively, and μ_t is turbulent viscosity given by

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \tag{5}$$

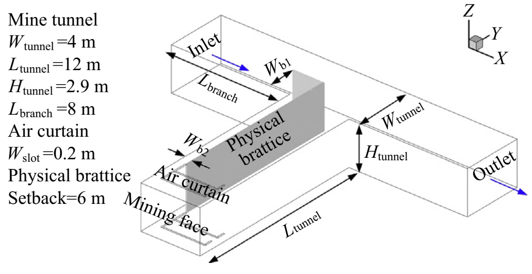

Fig. 1. Schematic view of an underground mine development region with a hybrid brattice installed.