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Numerical Study of simultaneous methane and coal dust dispersion in a room and pillar mining face

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ABSTRACT
In underground coal mines, uncontrolled accumulation of methane and fine coal dust often leads to serious accidents such as explosions. 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 the computational fluid dynamics (CFD) approach. Various possible scenarios of underground mine configurations are evaluated. The results indicate that solitary existence of a continuous miner adversely affects the airflow and leads to increases in both methane and dust concentrations. Nevertheless, it is found that the negative effects of a continuous miner presence on concentrations can be minimized or even neutralized by operating the scrubber fan on suction mode. In addition, it was found that the combination of scrubber fan on suction mode and brattice results in the best performance of methane and dust removal from the mining face.
KEYWORDS: dust; methane; mine ventilation; mining machine

1. INTRODUCTION

Coal mining is considered one of the world's most dangerous operations. There are many hazards associated with coal mining: explosion, structure collapse, hazardous gasses and particulates, moving vehicles, and lack of respirable air. Among these hazards, the most severe is explosion. Firedamp explosions, majorly caused by methane, can trigger more dangerous coal dust explosions, which lead to collapsed areas, trapped personnel, and worker death. Even in developed countries, coal related fatalities are considerably high. For example, more than one hundred thousand coal mine explosion fatalities have been recorded in the U.S. (U.S. Department of Labour, 2015). The situation is more alarming in developing countries, as indicated by the increase of the occurrences and casualties in China (Zheng, et al., 2009). This situation has encouraged the worldwide mining community to explore and evaluate solutions to reduce/eliminate the hazards causing the explosions. A vast number of studies have been conducted and reported. The majority of research has been focused on mine ventilation, as it directly affects the hazardous methane and dust accumulations in the mining face.

Pioneer studies on mine ventilation were directed at the fundamental aspect of mine ventilation. Kaliev and Akimbekov (1990) developed an air motion model based on Bernoulli equation and Runge-Kutta method. The results revealed that theoretical and experimental airflow rates differ by less than 10%. Riley and Edwards (1991) experimented on the methane drainage system in mining. It was found that the methane drainage system is more efficient at advanced mining as compared to that at retreat mining. Subsequently, computational fluid dynamics (CFD) are widely utilized in mine ventilation studies due to its capability to predict methane dispersion. Some examples are studies conducted by Srinivasa et al. (1993), Uchino and Inoue (1997), and Tomate et al. (1999).

Recently, research has been directed at exploring ventilation methods and designs. This is mainly attributed to the fact that fundamentals have been established and significant advancement in computational power allows CFDs simulations to be run at significantly reduced cost. Parra et al. (2006) examined ventilation near mining faces and found that blowing ventilation, in terms of dust control, offers better dust dispersion than exhaust ventilation if the setback distance is 6m or more. Wu et al. (2007) 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. Later, Torano et al. (2009) justified that simulations are consistent with experimental data, and also demonstrated that CFDs are necessary to analyze ventilation systems. Rodriguez and Lombardia (2010) found that different stone types

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result in different methane emissions. Sasmito et al. (2012) examined four different turbulence models: Spallart-Almaras, k-epsilon, k-omega and Reynolds Stress Model (RSM). It was found that the Spallart-Almaras model, which consumes the least computational power, would be sufficient to predict flow behavior. Another finding is that in typical room and pillar mining, flow stopping design can largely affect methane concentration. It is also found that the brattice-exhausting system leads to the lowest methane concentration. Kurnia et al. (2014) numerically examined the relation between methane sources and methane dispersion as well as methane distribution within the mining tunnel. Later, Kurnia et al. (2014) investigated intermittent ventilation systems and discovered a possible electricity saving plan. Zhou et al. (2015) simulated scenarios with the existence of a continuous miner. 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. Inhaling respirable dust can adversely affect workers' health. Moreover, high dust concentration can trigger dust explosions that be a disaster to the mine. The water spray system has been widely used due to its simplicity and effectiveness. As early as 1988, Aziz et al. discovered the system and thus, water is used to reduce dust content. Recent results show that water can reduce dust concentration up to 60% (Colinet et al., 2010). Tornao et al. (2010) extended their own research from methane to dust and developed a CFD model to match with field data. Wei et al. (2011) simulated different scenarios of different exhausting pipe locations and diameters to reduce dust concentrations. Dong et al. (2012) tested a methane-air explosion mechanism with the existence of coal dust and obstacles in a pipe, but lacked theory to explain the results. Zhou et al. (2013) investigated dust diffusion in a specific forced-exhaust hybrid tunnel with a continuous miner. Wang et al. (2015) also did similar dust investigation in a forced-exhausted hybrid tunnel for a rectangular-shaped laneway. Kurnia et al. (2014) investigated different ventilation tools on dust removal and energy saving perspectives and found that brattice generally have the best dust removing efficiency, at the cost of more energy consumption. Kurnia et al. (2015) investigated brattice setup and dust control in a typical mine tunnel. Hu et al. (2015) simulated respirable dust characteristics in another typical mine tunnel.

Many studies have investigated methane and dust concentrations separately. However, none of them have focused on the existence of both methane and dust despite them both being critical pollutants in coal mines. This study investigates the flow behavior and methane and dust dispersion characteristics in the mining face of an underground coal mine. Moreover, a continuous miner and also ventilation tools are included in the study since the mining machine takes up a very large area inside the active mining end, which is likely to cause flow changes (compared to scenarios without a 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 Figure 1. Ventilation air is supplied from inlet at a speed of 2 m/s. At the active mining face, methane js leaking into the tunnel at a speed of 0.002874 m/s and dust is generated by continuous miner at speed of 1 m/s with flow rate of 0.0062 kg/s. Detailed properties are summarized in Table 1.

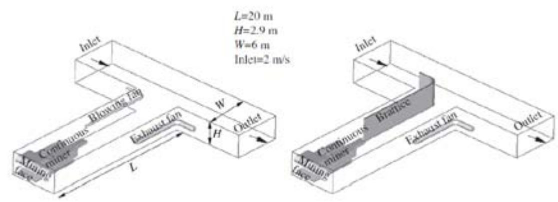

Figure 1: Schematics of mining face with mining machine and auxiliary ventilation: blowing-exhausting (left) and brattice-exhausting (right) (Kurnia, et al., 2014b).

Table 1: Geometric and operating parameters used.

Property	Value
Injection type	Surface (Mining surface)
Density (kg/m3)	1400 (Coal high value)
Diameter distribution	Rosin–rammler
Diameter range (m)	1×10-6 to 1×10-4
Mean diameter (m)	1×10-5
Spread parameter	2.78
Dust velocity (m/s)	1
Total flow rate (kg/s)	0.0062
Air curtain width (m)	0.2
Jet velocity (m/s)	12
Air velocity (m/s)	2
Tunnel height (m)	2.9
Tunnel length (m)	20
Tunnel width (m)	4
Brattice space (m)	0.5

For the sake of brevity, the mathematical formulation is not repeated here. The interested reader may refer to earlier publications (Kurnia et al., 2014a; Kurnia et al., 2014b) for details.

2.3 Boundary Conditions

The boundary conditions are prescribed as follows:

(i) Inlet: air flows into the tunnel is set to have velocity of 2 m/s
(ii) At the mining face: methane is released at total flow rate of 0.05 m^3/s and dust is generated at total flow rate of 0.0062 kg/s
(iii) At the outlet: stream-wise gradient of the temperature is set to zero and the pressure is set to standard atmospheric pressure (1 bar).
(iv) At walls: the standard wall function is used in all simulations.

3. RESULTS AND DISCUSSION

In this study, a total of nine possible scenarios are explored under both constant methane emission and dust emission from discrete sources. Table 2 illustrates the detailed case configurations and features with respect to their specific case numbers. For abbreviation purposes, only case numbers are presented in the figures afterward. The standard k-ε turbulence model is used in this study since it provides the required balance between computational time and accuracy. Flow validation for a similar geometry has been performed in another study (Kurnia, et al., 2014a).

Table 2 Cases with their features.

Case 1	No continuous miner, no ventilation tools
Case 2	Continuous miner with scrubber fan off, no ventilation tools
Case 3	Continuous miner with scrubber fan on injection mode, no ventilation tools
Case 4	Continuous miner with scrubber fan on suction mode, no ventilation tools
Case 5	Continuous miner with scrubber fan on suction mode, with ventilation fan blowing air into mining face
Case 6	Continuous miner with scrubber fan on suction mode, with ventilation fan sucking air out of mining face
Case 7	Continuous miner with scrubber fan on suction mode, with brattice installed
Case 8	Continuous miner with scrubber fan on suction mode, with brattice and suction fan
Case 9	Continuous miner with scrubber fan on suction mode, with blowing fan and suction fan

Figure 2 shows the velocity distribution at the mining face for cases 1 to 4. Previous work by Sasmito et al. (2013) shows that for cases with no auxiliary ventilation, the ventilation air is unable to reach the mining face. The same trend is observed in the present study, as reflected in Figure 2a. As mining machinery is added, the flow behavior at the face changes. Figure 2b demonstrates that the presence of machinery presents flow obstruction thus inducing flow separation resulting in increased recirculation. Case 3 depicts the flow field with the scrubber fan turned on, which creates high air velocity flows to the face. Closer inspection reveals that the blowing air from the scrubber is not sufficient to push air leaving the working area and thus creates a recirculation zone (Figure 2c). In Case 4, on the other hand, the scrubber fan is in exhausting mode and is found to be able to provide sufficient flow from mining face to the laneway tunnel, and thus no recirculation is observed.

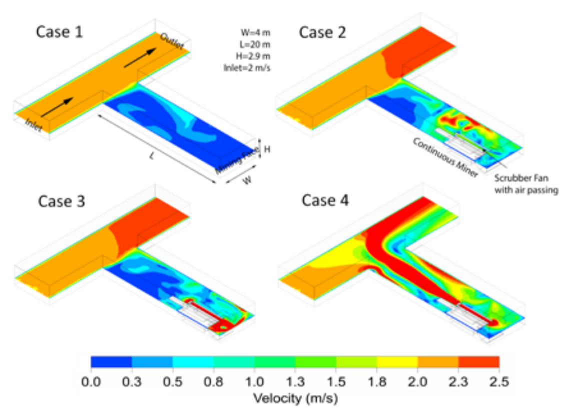

Figure 2: Velocity contour at height of 1 m from the tunnel floor.

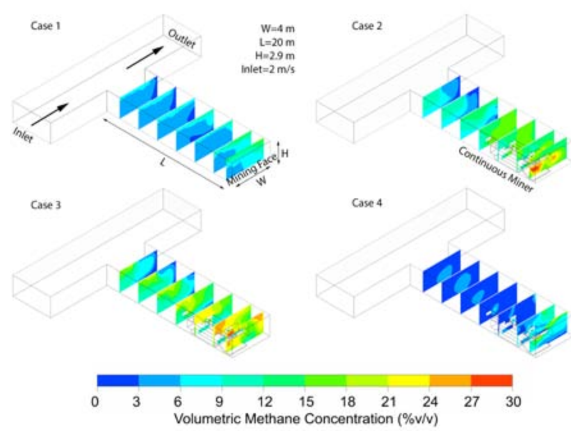

Figure 3: Contour of methane concentrations at 1 m, 3 m, 6 m, 9 m, 12 m, 15 m, 18 m away from mining face.

The presence of recirculation flow, mining machinery and a scrubber fan is expected to have a direct impact on methane and dust distributions. Figure 3 shows the distribution of methane concentration along the active mining tunnel. For instance, the presence of mining machinery and recirculation flow increases methane distribution at the face as can be inferred from Figure 3a, 3b, and 3c. Case 2 is found to have highest methane concentration, whereas the lowest methane concentration is found in Case 4 where the scrubber fan is in exhausting mode. Note that as compared to earlier work by Sasmito et al (2013), the methane concentration in this case is up to 30% higher. This discrepancy can be attributed to the fact that the mining tunnel used in this study is longer (20 m) as compared to 12 m used in Sasmito et al. (2013). Hence, it can be concluded that extra length in active room and pillar mining significantly reduces ventilation efficiency.

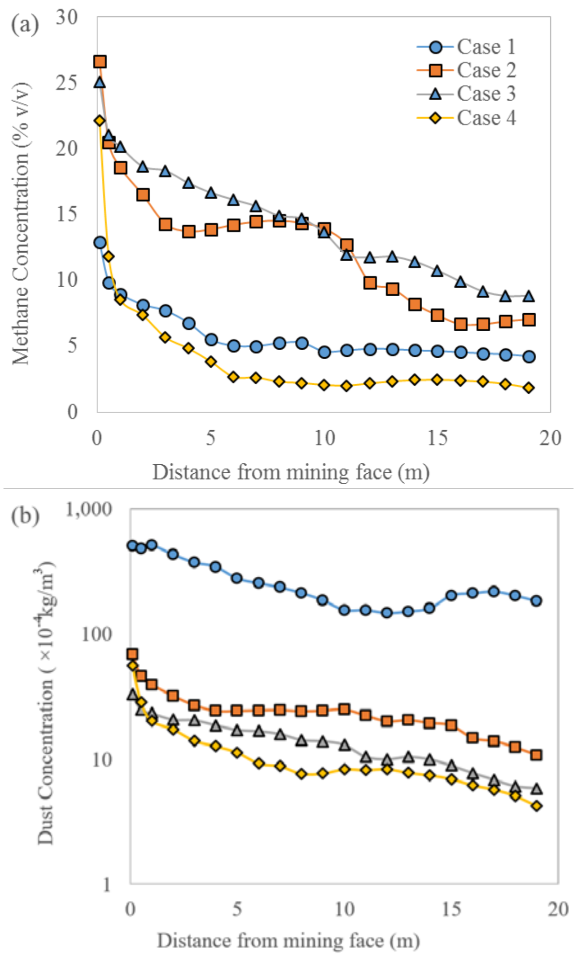

Figure 4: (a) Average methane concentration, (b) Average dust concentration, along the tunnel.

Figure 4a presents the average methane concentration at various distances along the tunnel. The result clearly demonstrate that Case 4, where the fan is in suction mode, provides the best effectiveness in terms of low methane concentration. The percent increase in methane concentration for Cases 2 and 3 is quite significant as compared to Case 1. It is because a continuous miner takes up a large space in the tunnel and obstructs ventilation air which results in smaller volume in the active mining tunnel resulting in increased methane concentrations. Trends in Figure 4a also reveal that Case 3, in which the scrubber fan is turned on in blowing mode, increases the concentrations in the mining tunnel as compared to Case 2 where the scrubber fan is turned off. This can be explained by the fact that a blowing fan creates stronger recirculation flow while it is unable to push the methane out towards the main tunnel. Therefore, Case 3 is non-effective or can even be concluded as counter-productive to reduce methane concentration in the tunnel. Conversely, Case 4 is found to be beneficial in reducing methane concentration.

The average dust concentration along the tunnel is presented in Figure 4b. Case 1 shows the highest dust concentration among others, as there is insufficient airflow to remove dust from the mining face. The cases with a continuous miner in general yield lower dust concentration due to higher flow recirculation, which somehow is effective in dispersing the dust. Case 2, in contrast to methane control, gives rise to the dust concentration, as there is no auxiliary ventilation turned on. Case 3 with a blowing scrubber fan has a positive effect on dust control, however the exhaust scrubber fan performs best in mitigating dust concentration.

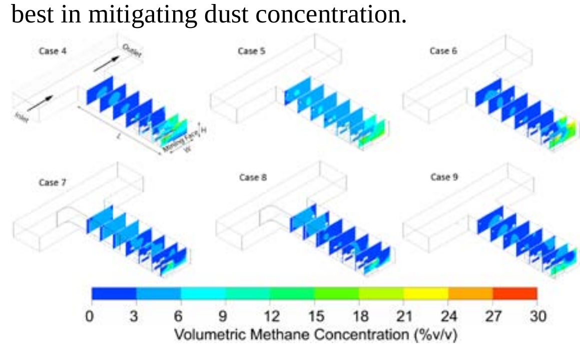

Figure 5: Contour of methane concentrations at 1 m, 3 m, 6 m, 9 m, 12 m, 15 m, 18 m away from mining face.

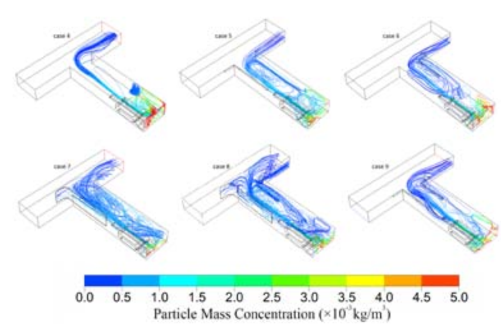

Figure 6: Air outflow from mining face, colored by dust concentration.

Figure 5 shows the performance with regard to methane concentration for Cases 4 to 9. Note that all the cases in Figure have the continuous miner on suction mode and Case 4 serves as the base case to the rest of Cases 5 to 9. Compared to Case 4, Case 5 is found to be counter-productive as it yields higher methane concentration due to recirculation flow created by an additional blowing auxiliary fan. This observation is mirrored in Figure 6b. Case 6 is effective in reducing methane at 6-20 m range from mining face but it is found less effective in reducing the most critical area at the mining face due to recirculation flow (Figure 6c). Cases 7, 8 and 9 are relatively effective in reducing methane concentration close to the mining face, which can be attributed to there being no recirculation flow in the working area for these cases.

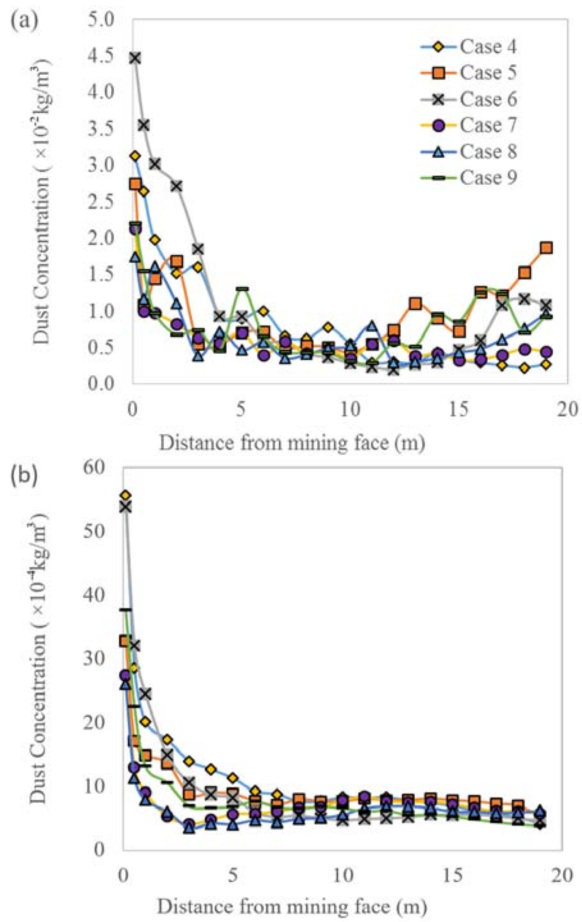

Figure 7: (a) Maximum dust concentration and (b) Average dust concentration along the tunnel.

Looking at the maximum and average dust concentrations, **Error! Reference source not found.** reveals that the maximum dust concentration is about one order-of-magnitude higher than that of average concentration. From the maximum dust concentrations (Figure 7a), Case 7 gives the best dust removal ability followed by the blowing-exhaust configuration (Case 9) and brattice-exhaust (Case 8). From the average dust concentration perspective, Figure 7b shows that brattice exhaust configuration (Case 8) performs best in removing dust from the mining face, followed by brattice, which has a slightly inferior performance.

4. CONCLUSIONS

A three-dimensional CFD model for a mining face with mining machinery and auxiliary ventilation have been developed and presented. To take into account the turbulence effect, the standard k-epsilon model is used and selective computational results for nine different cases are presented. The effect of a continuous miner presence as well as additional ventilation are evaluated and discussed with the focus being methane and dust dispersion and accumulation.

Several important findings of the study are that (i) higher air flow rate generally yields lower methane and dust concentrations (ii) the presence of a continuous miner negatively impacts the airflow in active mining tunnel and increases concentrations by taking up a large volume in the tunnel and blocking almost half of the tunnel section area, and (iii) a scrubber fan turned to suction mode could counter the continuous miner impact by reducing a significant amount of methane and dust.

Moreover, it is found that brattice cases (Cases 7 and 8) along with the blowing exhaust case (Case 9) are more effective in reducing methane and dust concentrations whereas the solo use of blowing or exhausting fan is not effective. Future studies will be focused on reducing methane concentration to even lower levels as current cases contain quite high levels of methane at places near the mining face. In addition more tunnel geometries will be evaluated and filters for fans will be added into the simulation model to investigate their effectiveness in reducing dust concentrations.

5. ACKNOWLEDGEMENT

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