

Numerical studies of ventilation effect on methane layering behaviour in underground coal mines

Pradeep Kumar, Devi Prasad Mishra*, Durga Charan Panigrahi and Patitapaban Sahu

Department of Mining Engineering, Indian Institute of Technology (Indian School of Mines), Dhanbad 826 004, India

Layering of methane in underground coal mines owing to poor ventilation leads to methane explosion hazard. We study the methane layering phenomenon and the effect of ventilation on dispersion of methane in underground coal mines at air velocities varying from 0.5 to 4.0 m/s. Three-dimensional simulations using CFD code ANSYS Fluent 12.0 were performed assuming the flow to be unsteady, turbulent and incompressible. The study demonstrated that ventilation significantly affects the behaviour of methane layering and dispersion of methane in underground coal mines. The layering length decreased with increase in air velocity. At air velocity of 4.0 m/s, the methane layering length considerably reduced to a safer level of about 1 m. Moreover, the simulation results showed a good agreement with the experimental results.

Keywords: Methane layering, numerical simulation, underground coal mine, ventilation effect.

UNDERGROUND coal mining activities are associated with methane (CH₄) gas emission from the coal seams and adjoining gassy formations. Methane concentration in underground coal mines primarily depends on the degree of gassiness of coal seams and adjoining formations, geological conditions, productivity of mines and operational variables¹. Methane is a highly inflammable gas, explosive when its concentration in air lies in the range 5%–15%. Incidences of coal mine explosions due to ignition of methane have been widely reported^{2–4}. Therefore, emission of methane into underground coal mines raises concern regarding adequate ventilation to ensure safety in the mines.

In India, a large number of underground coal mines are gassy and methane emission in those mines is a problem⁵. However, studies related to gassy coal mines have not been widely conducted in India. Banerjee *et al.*⁶ developed a mathematical model for estimation of methane inflow from gassy coal seams into longwall workings. Banerjee⁷ presented some case studies on methane emission problems in Indian coal mines. Banerjee and Dhar⁸

discussed the methane emission issues in gassy underground coal mines in India and the options for reducing emission to the atmosphere. They suggested that pre-mining degasification from virgin coal seams is the best option for reducing methane emission, increasing mine safety and recovery, and commercial utilization of methane.

Methane, being lighter than air with specific gravity of 0.554, tends to stratify near the roof level of mine galleries. The effective length of methane layer is the distance from the source to a point where mean concentration of methane in the layer is 5% (ref. 9). Raine¹⁰ defined methane layer as an accumulation ‘containing methane percentage within or above the explosion range of firedamp (i.e. 5% or over)’, thus relating it to the hazard. The stability and length of methane layers are indicated by the dimensionless layering number (L), which is given by the following equation¹¹

$$L = \frac{v}{\left\{ g \frac{\Delta\rho}{\rho} \frac{Q}{W} \right\}^{1/3}}, \quad (1)$$

where g is the acceleration due to gravity (m/s²), $\Delta\rho$ the density difference of air and methane (kg/m³), ρ the density of air (kg/m³), v the average air velocity (m/s), Q the amount of methane emitted into airway (m³/s) and W is the width of the airway (m).

From eq. (1), it is evident that layering of methane is more pronounced in underground openings with high methane emission and poor ventilation. In horizontal airways, layering number of five or more causes a sharp decrease in methane layer length and hence is regarded as a safe value. According to the National Coal Board (NCB), UK¹², layering number of 2 or less indicates the need for monitoring to confirm the absence or presence of layering, and where possible, a value of 5 should be used for preventing methane layering.

The phenomenon of methane layering has been a subject matter for many studies in order to understand the concept and find effective means for breaking it^{13–19}. Till today, the pioneering study on methane layering by Bakke and Leach^{11,16} during 1960s in the UK is being

*For correspondence. (e-mail: devi_agl@yahoo.com)

relied upon and referred by researchers. Dispersion of methane layering has been a challenging task for the ventilation engineers for maintaining safe working condition inside underground coal mines. Several methods are used for dispersion of methane layering; however, adequate and continuous ventilation is considered as the most effective among them. The regulations in India specify minimum air velocity of 1.25 m/s for adequate ventilation at the maximum span of a longwall face in underground coal mines of degree III gassiness²⁰, however, the maximum air velocity has not yet been stipulated. Based on the experience in the country as well as standards adopted by other countries like the UK, Poland and USSR, the Directorate General of Mines Safety (DGMS) Circular (Cir. 42/1974) recommended the maximum air velocity of 4 m/s for longwall faces in India.

There is plenty of scope for studying the behaviour of methane layering and its dispersion. Methane is a colourless gas and hence studying methane layering behaviour with naked eyes is not possible. Computational fluid dynamics (CFD) software is a useful tool that not only enables simulation of methane layering phenomenon, but also its visualization. It has been used by many researchers to simulate the ventilation airflow in underground mine roadways and tunnels^{21,22}. However, studies on the application of CFD for simulation of methane layering in underground mine openings are limited. Kurnia *et al.*²³ carried out CFD simulations on dispersion of methane in underground coal mining faces with auxiliary ventilation. Torano *et al.*²⁴ conducted CFD simulations to study the methane behaviour in auxiliary ventilation of a deep underground coal mine. Here, we study the behaviour of methane layering and effect of ventilation on methane dispersion in a retreating longwall mine using CFD simulations.

Methodology

In this study three-dimensional CFD simulations of methane layering in tailgate of a retreating longwall panel

were performed using CFD code ANSYS Fluent 12.0 at various air velocities. The main aim was to study the effect of ventilation on the behaviour of methane layering and dispersion of methane. Figure 1 shows the layout of a typical retreating longwall panel. From this figure it may be observed that methane released from different sources such as broken coal, floor, roof, goaf, cracks, etc. get mixed up with ventilating air and is exhausted to the main return through the tailgate. The air velocity was varied in the range 0.5–4.0 m/s at 0.5 m/s intervals and methane emission rate into the tailgate was assumed 30 m³/min for the simulations. The maximum and average methane concentrations in the tailgate at 5 m intervals were measured at each air velocity. In addition, the methane layering length at each air velocity was determined from the CFD simulations. It may be reiterated that the distance starting from the goaf edge (source of methane emission) to the point where the mean concentration of methane in layer is 5% is considered as the length of methane layer. Finally, a comparison between the simulation results and the experimental results was made.

Geometry creation and meshing of computational domain

A three-dimensional model of a retreating longwall mine consisting of an arch-shaped horizontal tailgate of 90 m length starting from the goaf edge and a part of the longwall face of rectangular cross-section was considered for CFD simulations. Figure 2 shows the geometry of flow domain indicating the dimensions of the tailgate. The meshing of the geometry was done using hex mesh cells. Initially, a grid independence study was conducted with three sets of cell numbers, viz. 1.2, 1.8 and 2.4 million and the simulation results in terms of methane concentration were compared to ensure a mesh-independent solution. About 10% deviation in the result with 1.2 million cells was observed compared to the finest mesh of 2.4 million cells, whereas the deviation was less than 1%

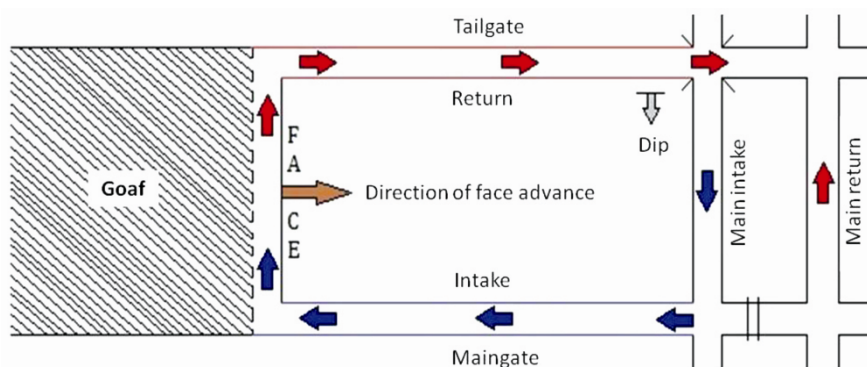


Figure 1. Plan view of a typical retreating longwall panel.

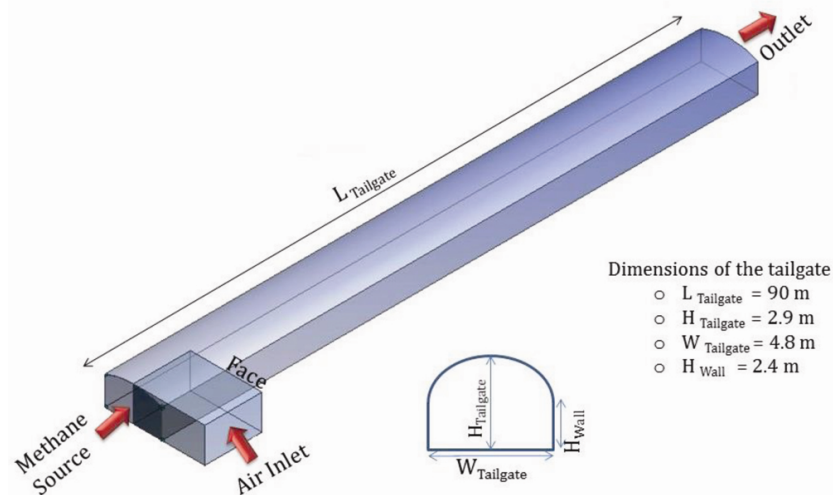


Figure 2. Geometry of the tailgate and part of the longwall face.

with 1.8 million cells compared to the finest mesh. Since no significant difference in the simulation results was observed with cell numbers of 1.8 and 2.4 million, a grid consisting of around 1.8 million cells was finally chosen for meshing of the geometry.

CFD simulation

The CFD simulations were performed using three turbulence models, viz. Spalart–Allmaras, standard $K-\omega$ and $K-\omega$ (SST) commonly used for similar kinds of studies^{23,24}. The purpose was to compare the variation in results obtained using different models and recommend a suitable model for this type of study. The flow was assumed to be three-dimensional, unsteady, turbulent and incompressible. Since the simulation involved methane and air, we considered the gravity effect and multiphase flow modelling in which air was selected as the primary phase and methane as the secondary phase. The boundary conditions for wall, air inlet, methane inlet and air outlet were set as shown in Figure 2. The air outlet was set with the atmospheric pressure condition. The friction factor and roughness constant for the tailgate were determined as 0.066 and 0.04 respectively, using the actual roughness value of the tailgate and Moody's diagram²⁵. During iterations, a convergence value of 1E-06 was set for obtaining accurate results.

Results and discussion

Variation of air velocity and methane concentration in tailgate

Dispersion of methane in the tailgate greatly varies depending upon the variation in air velocity and turbulent

mixing along and across the tailgate. Figure 3 presents the velocity vectors illustrating air velocity variations in tailgate for three ranges such as minimum (0.5 m/s), moderate (2.0 m/s) and maximum (4.0 m/s) obtained through simulations using the $K-\omega$ turbulence model. From the figure it can be seen that airflow in the tailgate follows a similar trend for all the velocity ranges; however, the flow is found to be non-uniform along and across the tailgate. At the beginning of tailgate, the flow is more non-uniform with greater variation in air velocity and thereafter, it becomes more or less streamlined. Near the bend portion (junction of longwall face and tailgate), a zone of turbulence causing greater turbulent mixing of methane and air stagnation zones resulting in the accumulation of methane can be noticed.

The variation of methane concentration in tailgate at different air velocities was analysed from the contours of methane volume fractions obtained from simulations using $K-\varepsilon$, $K-\omega$ and Spalart–Allmaras turbulence models. For example, Figure 4 shows the contours of methane concentration obtained from the $K-\varepsilon$ model at three ranges of air velocity, i.e. minimum (0.5 m/s), moderate (2.0 m/s) and maximum (4.0 m/s). From the contours at lower air velocities, occurrence of methane layering in the tailgate can be clearly observed. Highest methane concentration in the layer is found near the roof level, which gradually decreases downward due to dilution with ventilating air. Similarly, Figure 5 shows the contours of methane concentration at 10 m intervals from the goaf edge obtained using $K-\varepsilon$ model at air velocities of 0.5, 2.0 and 4.0 m/s. This figure indicates a decrease in length and thickness of the methane layer with increase in air velocity. Also, because of turbulent dispersion, a gradual decrease in methane concentration with distance from the goaf edge is noticed in tailgate.

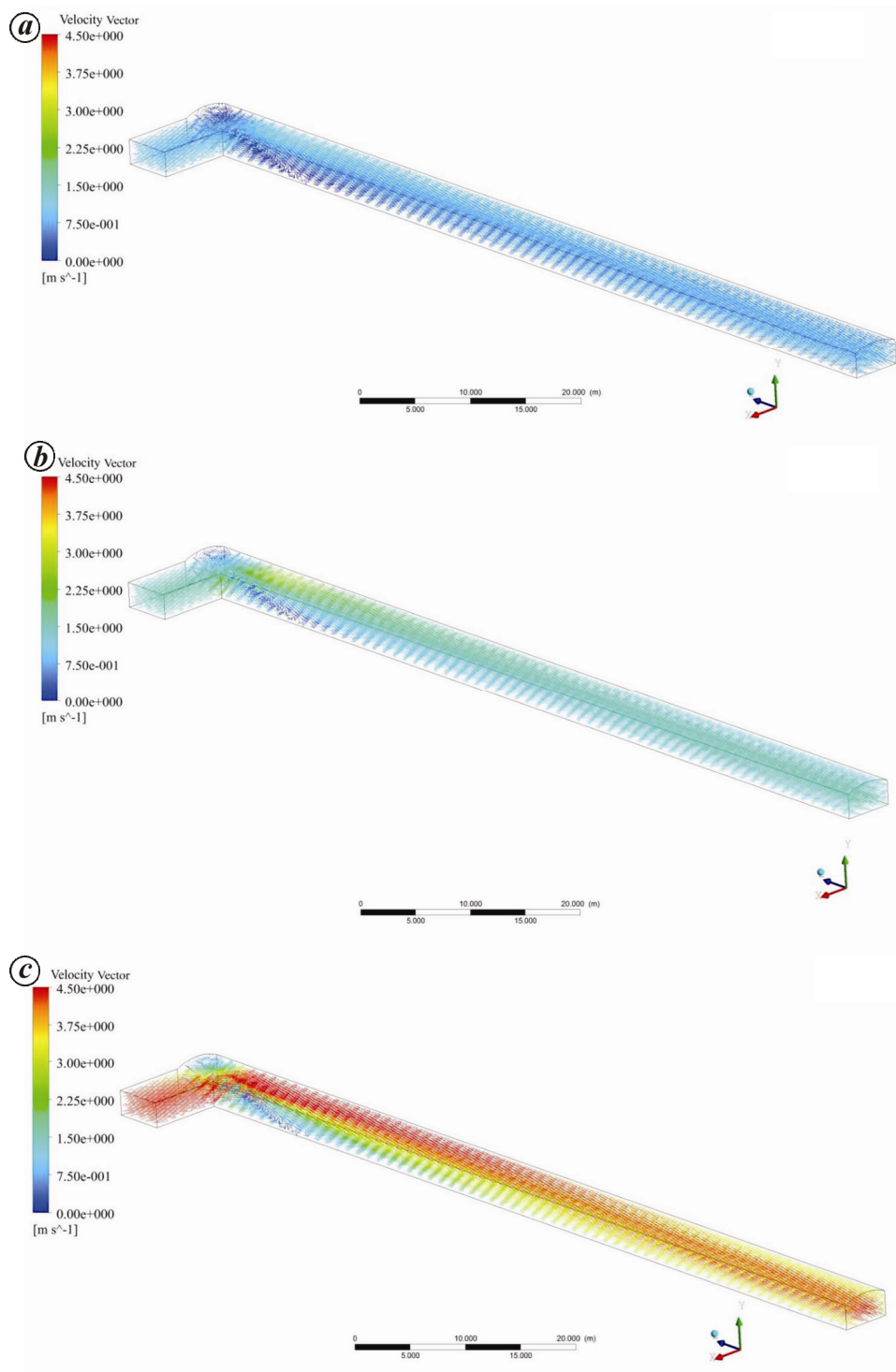


Figure 3. Velocity vectors in the tailgate at air velocities of (a) 0.5, (b) 2.0 and (c) 4.0 m/s.

Figures 6 and 7 show the variations of maximum and average methane concentrations at 5 m intervals in the tailgate at various air velocities obtained by three turbulence models respectively. Decrease in maximum and average methane concentrations with increase in air velocity as well as distance from the goaf edge can also be noticed from these figures. At 10 m distance, the maximum meth-

ane concentrations at air velocities of 0.5 and 4.0 m/s are found to be 47.2% and 6.1%, 59.9% and 9.7%, and 43.84% and 7.7% for the Spalart–Allmaras, $K-\epsilon$ and $K-\omega$ models respectively, whereas at 90 m distance the respective maximum concentrations are found to be 19.1% and 0.2%, 25.6% and 0.4%, and 22.3% and 0.8%. Similarly, at 10 m distance, the average methane concentrations at air

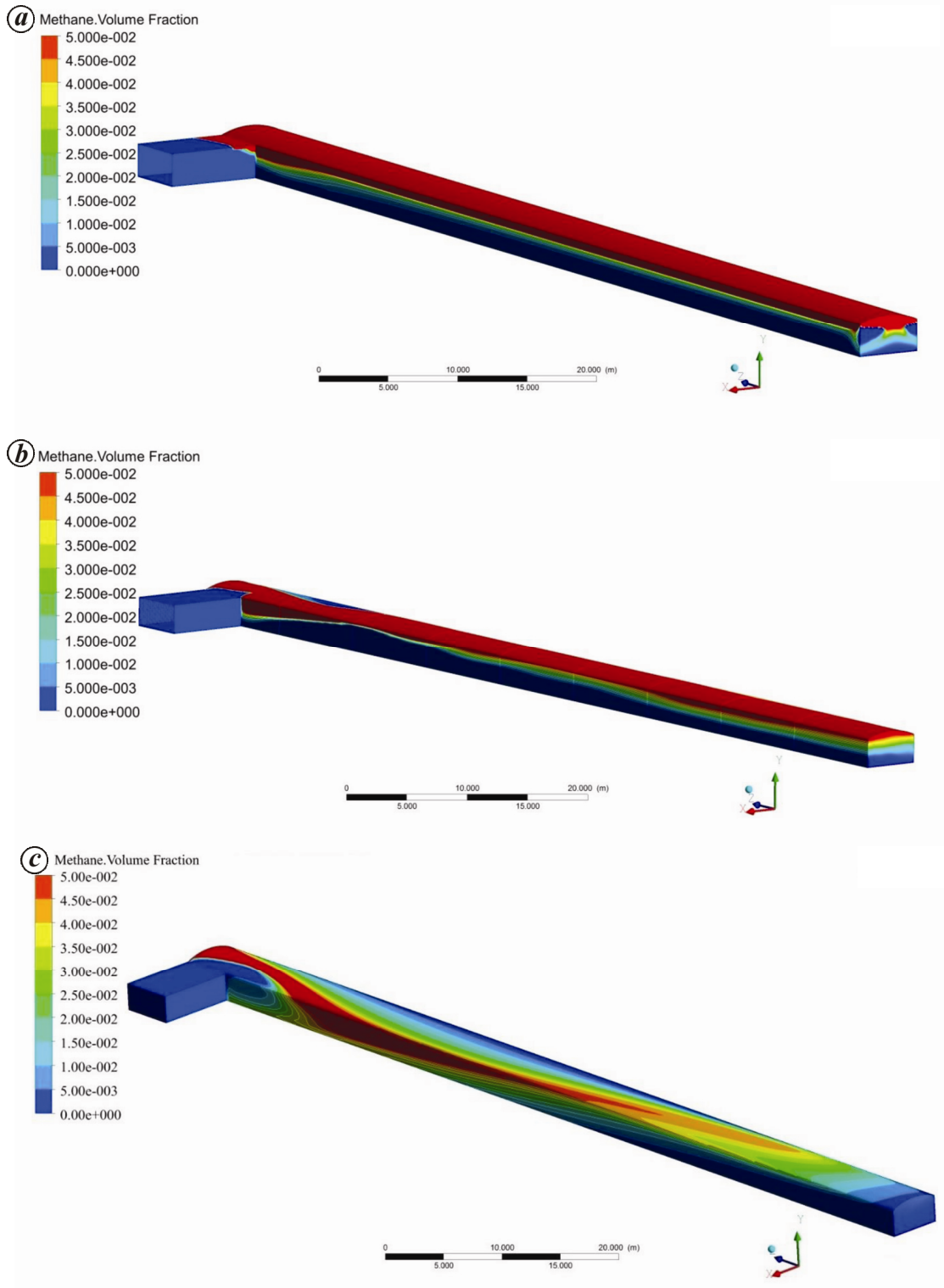


Figure 4. Contours of methane concentration obtained by $K-\varepsilon$ model at air velocities of (a) 0.5, (b) 2.0 and (c) 4.0 m/s.

velocities of 0.5 and 4.0 m/s are 9.9% and 1.1%, 10.6% and 0.9%, and 10.4% and 1.08% for the Spalart–Allmaras, $K-\varepsilon$ and $K-\omega$ models respectively, whereas at a distance of 90 m, the respective average concentrations are to be 4.5% and 0.1%, 5.4% and 0.12%, and 5.4% and

0.22%. At velocity of 4.0 m/s, while maximum methane concentration in the layer reduces below 1% at a distance of 85 m from the goaf edge in the Spalart–Allmaras model, the concentrations at the same distance are found to be 1.2% and 1.5% respectively, in the $K-\varepsilon$ and $K-\omega$

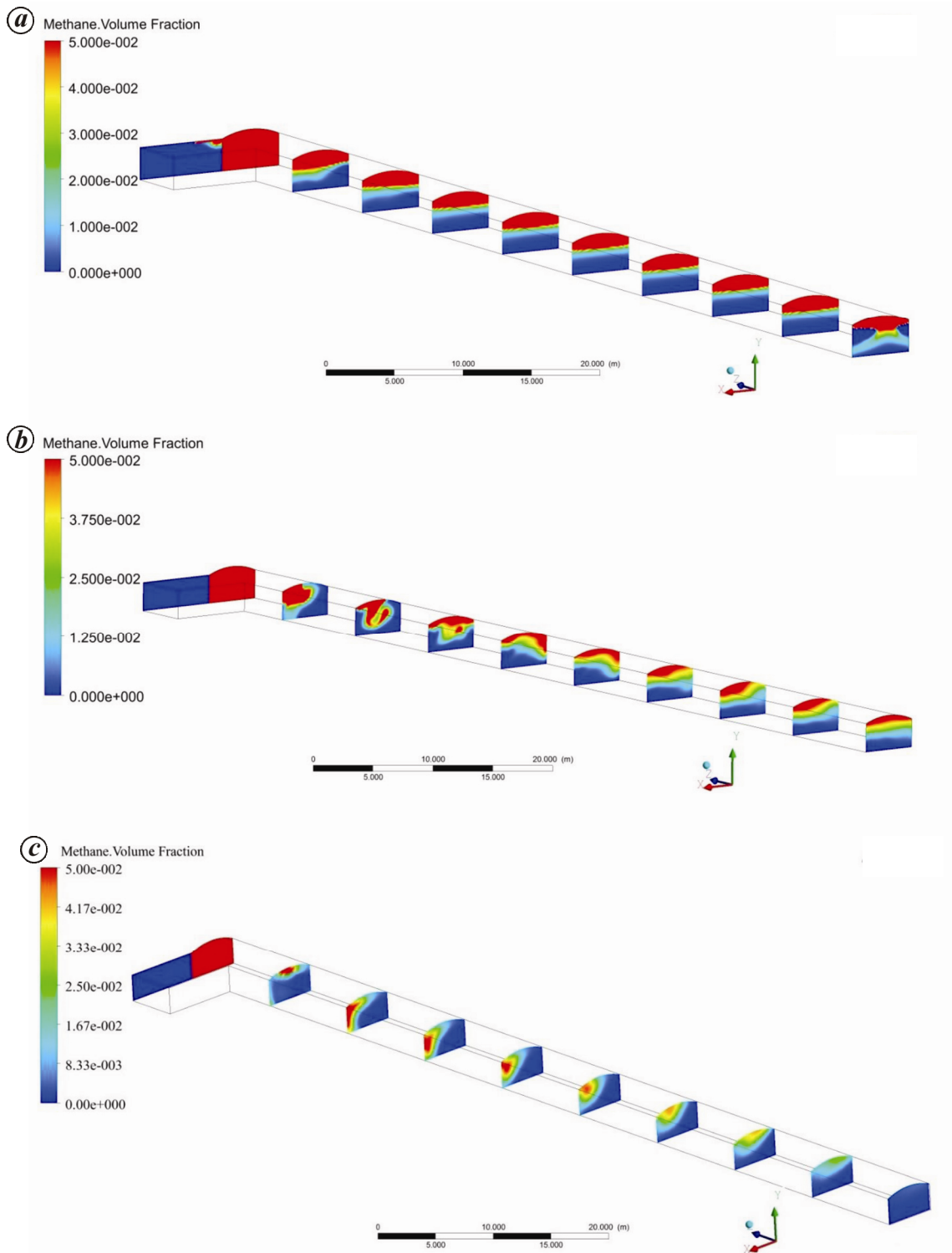


Figure 5. Contours of methane concentration at 10 m interval segments from the goaf edge obtained by $K-\epsilon$ model at air velocities of (a) 0.5, (b) 2.0 and (c) 4.0 m/s.

models. Similarly, while the average methane concentration in the layer at 4.0 m/s air velocity is 1% at 65 m distance in the Spalart–Allmaras model, the concentrations at the same distance are found to be 1.11% and 1.1% respectively, in $K-\epsilon$ and $K-\omega$ models.

The simulation results obtained from the three turbulent models used in this study were further compared. The results show that the average methane concentrations predicted by the $K-\epsilon$ and $K-\omega$ models closely match, whereas the Spalart–Allmaras model predicts a lower

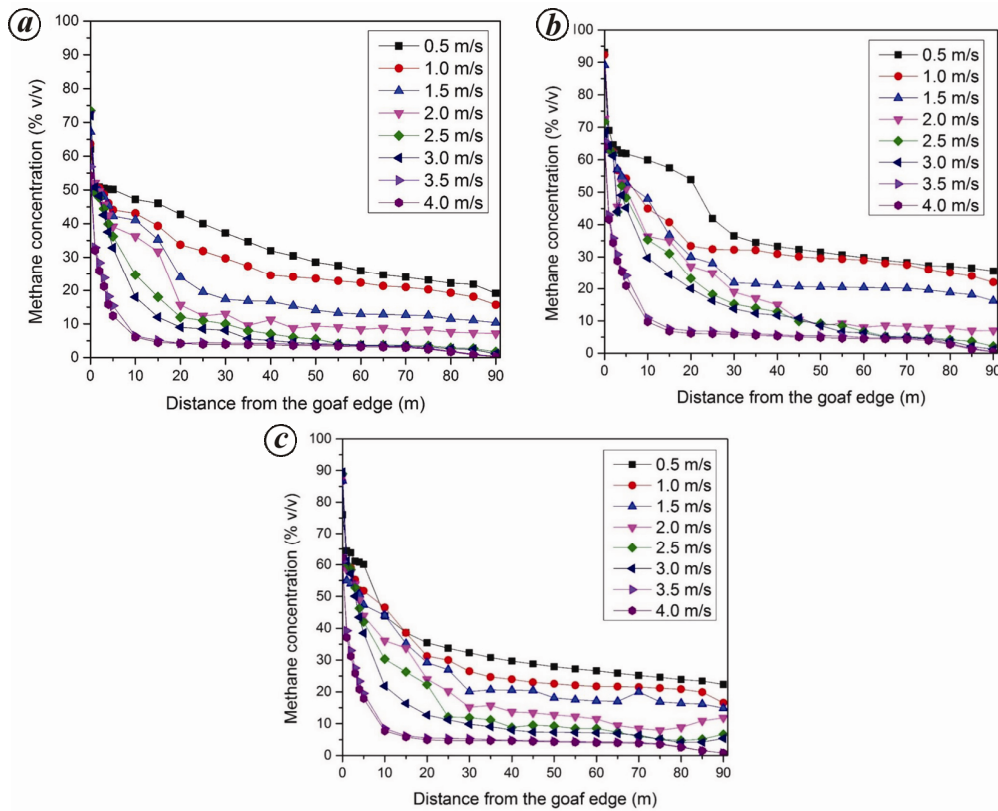


Figure 6. Maximum methane concentration in the layer at 5 m intervals from the goaf edge at different air velocities obtained by (a) Spalart-Allmaras, (b) $K-\epsilon$ and (c) $K-\omega$ models.

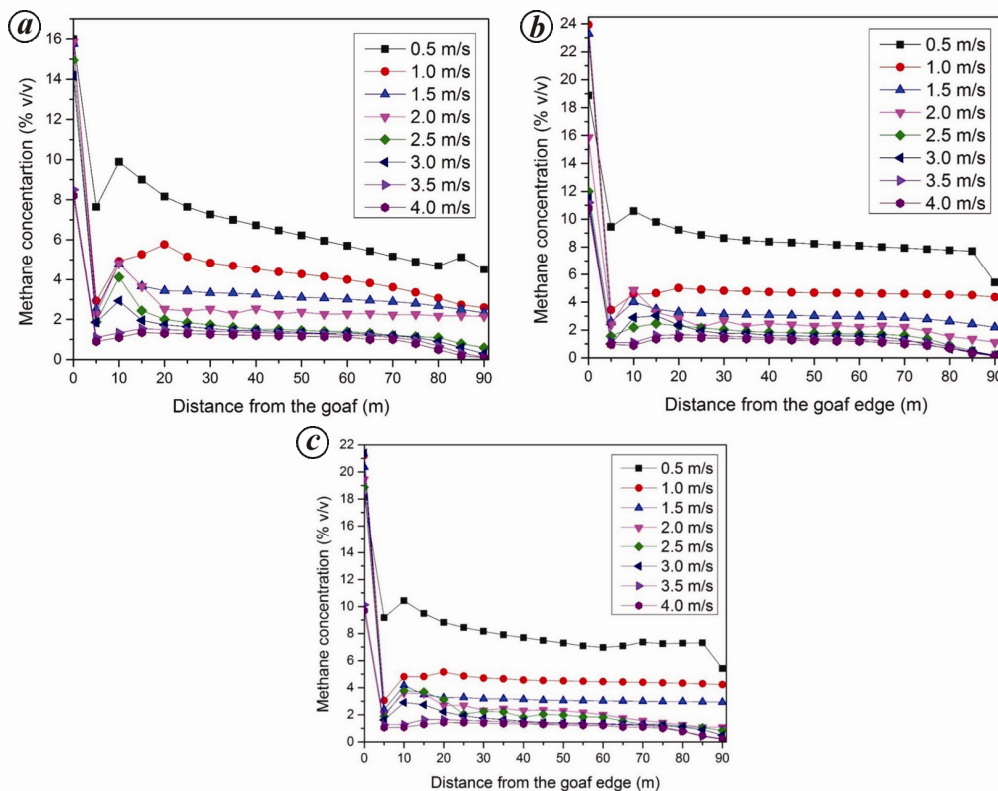


Figure 7. Average methane concentration in the layer at 5 m intervals from the goaf edge at different air velocities obtained by (a) Spalart-Allmaras, (b) $K-\epsilon$ and (c) $K-\omega$ models.

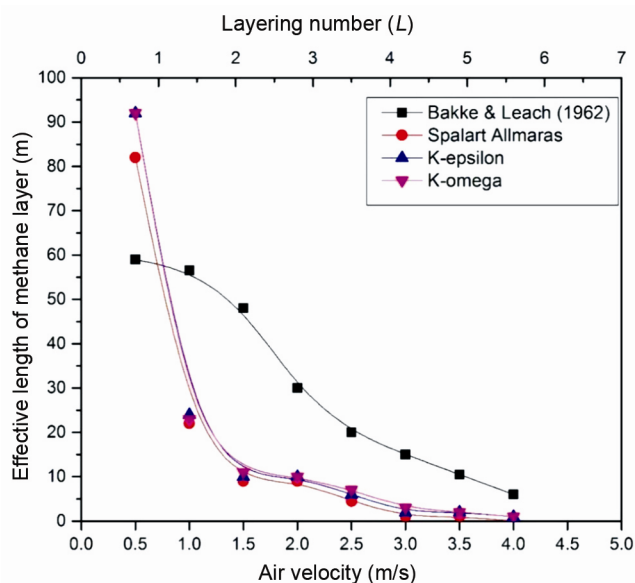


Figure 8. Variation of methane layer length with air velocity and layering number.

average methane concentration compared to the former two models. Therefore, it is evident that Spalart–Allmaras model causes the highest turbulence effect and hence predicts the lowest average methane concentration in the layer at different air velocities. However, a small difference is observed between the results obtained by $K-\epsilon$ and $K-\omega$ models.

Variation of methane layering length in tailgate

Figure 8 shows the variation of methane layering length in tailgate at different air velocities. It can be clearly observed that layering length follows a decreasing trend with air velocity, as expected. Among the three turbulence models, the layering lengths predicted by $K-\epsilon$ and $K-\omega$ models closely match, however, Spalart–Allmaras model slightly underestimates the layering length. The reason for this may be due to greater methane dispersion effect of the model.

From Figure 8 it can also be observed that at the lowest air velocity of 0.5 m/s, while both $K-\epsilon$ and $K-\omega$ models predict methane layering length of about 90 m, the Spalart–Allmaras model predicts a layering length of about 85 m. At 1 m/s air velocity, the length of methane layer sharply reduces to about 27 m and at 4.0 m/s, it diminishes to about 1 m. This suggests that 4.0 m/s air velocity is good enough for dispersing methane to a safer level in tailgate of a gassy longwall mine. Therefore, it is envisaged that the behaviour of methane layering in underground coal mines is greatly influenced by ventilation, although other variables such as emission rate of methane and width of tailgate also play a role. It may be mentioned here that for a particular air velocity and width of

airway, the layering length will be greater at higher methane emission rates and vice versa. Similarly, for a particular air velocity and methane emission rate, the layering length will be greater at a lower airway width due to lesser airflow.

It has been already mentioned that the layering number is used to confirm the sufficiency of ventilation, and also used as an alternative means for estimating air velocity required to prevent methane layering in underground coal mines¹³. Therefore, the simulation results of this study were compared with the experimental results of NCB¹² in terms of methane layering number proposed by Bakke and Leach¹¹. In addition, the methane layering lengths predicted by different turbulence models at different air velocities were compared with those obtained by Bakke and Leach¹¹. Figure 8 shows a comparison of simulation results with experimental data of Bakke and Leach¹¹. This figure clearly shows that the layering lengths predicted through simulations follow a decreasing trend with increase in air velocity and layering number, which is similar to the trend obtained by Bakke and Leach¹¹. The layering number corresponding to 4.0 m/s air velocity estimated for methane dispersion, 30 m³/min methane emission rate and 4.8 m gallery width was calculated to be 5.21 using eq. (1), which is more than the desired layering number value of 5 for preventing methane layering^{11,12}. In addition, at 4.0 m/s air velocity, the layering length predicted through simulations reduced to about 1 m against the experimental value of 6 m obtained by Bakke and Leach¹¹. This confirms that 4.0 m/s air velocity is sufficient to disperse methane to a safer level and avert methane layering in the tailgate. Hence, it is apparent that the CFD simulation results corroborate the experimental data.

From Figure 8 it can also be seen that among the three turbulence models, the layering lengths predicted by the $K-\epsilon$ and $K-\omega$ models closely match; whereas the Spalart–Allmaras model slightly underestimates the layering length. Comparatively, the methane layering lengths values predicted by the $K-\epsilon$ and $K-\omega$ models are found to be closer to the experimental values of Bakke and Leach¹¹. Hence, the $K-\epsilon$ and $K-\omega$ models may be preferably used for studying the methane roof-layering behaviour. However, the $K-\epsilon$ model would be the most preferable one because other researchers have also obtained good correlation between the measured and predicted results using this model for simulation of ventilation airflow and methane dispersion in tunnels and underground roadways^{21,23,24,26}.

Conclusions

The study of methane roof layering phenomenon is essential for taking appropriate measures for preventing methane explosion in underground coal mines. Since it is not

possible to observe methane layering with the naked eye, studying its behaviour in the mines is difficult. Moreover, accurate study of methane layering in the laboratory and obtaining comparable results are also equally difficult due to complexities involved in fabricating the experimental set-up and experimentation. Therefore, CFD modelling is an effective means of studying the methane layering behaviour in underground coal mines with reasonable accuracy. Here we studied the behaviour of methane layering and the effect of ventilation on dispersion of methane at varied air velocities through CFD simulations using $K-\varepsilon$, $K-\omega$ and Spalart–Allmaras turbulence models. At air velocity of 4 m/s, the methane layer length in the tailgate of longwall mine significantly reduces to about 1 m. It is concluded that ventilation plays a vital role in dispersion of methane to safer level in underground coal mines.

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