Lattice Boltzmann simulation of the methane backward flow in coal mine tunnels after methane outburst

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Abstract. Numerical study of the methane backward flow in coal mine tunnels after a methane outburst is necessary to the engineering design and emergency rescue. In this paper, we introduce Lattice Boltzmann Method (LBM) coupled with the Large Eddy Simulation (LES) model to simulate the methane backward flow in the air-intake tunnel of twin-tunnel construction in the coal mine after the methane outburst and analyze the effects of the inlet air velocity, the intensity of the methane outburst and the width of the tunnel to the distance that the methane can flow backward. It demonstrates that with the increase of the inlet air velocity, the distance that the methane can flow backward decreases. With the increase of the intensity of the methane outburst, the distance that the methane can flow backward increases. There exist linear relationships between the inlet air velocity, the intensity of the methane outburst and the distance that the methane can flow backward. The change of the tunnel width has almost no influence on the distance that the methane can flow backward.

1. Introduction

The methane in coal bed emits to the tunnel when tunneling in the underground coal mines. The “methane outburst” is the phenomena that extremely large amounts of coal-bed methane emits to the coal mine tunnel in an extremely brief period. This period can be divided into two stages. In stage one, the coal-bed methane desorbs from the coal body and damages the original coal body structure. In stage two, the coal-bed methane burst into the tunnel and interact with the underground air [1]. Numerous violent methane outbursts have occurred in underground coal mines worldwide, sometimes with fatal consequences for workers. When the methane outburst does not occur, the ventilation system of the coal mine can dilute the methane below the critical concentration which may cause the explosion and asphyxiation accidents [2,3]. However, after methane outburst, the fresh air provided by the ventilation system will not be enough to dilute the methane and even the air flow state will be changed.

Figure 1(a) shows the main network of the ventilation system in a coal mine. Under the action of the main fan, the fresh air flows through the intake-air shafts, the main intake-air tunnels, the intake-air tunnels of the coal face, the coal face, the return-air tunnels of the coal face, the main return-air tunnel and the return-air shafts in sequence. The air that has not yet flowed through the coal face is regarded as fresh air. The air is polluted by the emitted methane, dust and other harmful gas when it flows through the coal face. The region with fresh air is safer than the region with polluted air. Most of the workers and equipment are in the region with fresh air. The blue region in figure 1(a) represents
the region with fresh air and the yellow region represents the region with polluted air.

Figure 1. The ventilation system in a coal mine. (a) The main network of the ventilation system and (b) The local ventilation system of the twin-tunnel.

Methane outburst most likely occurs in the heading face of the coal mine tunnel. Twin-tunnel construction is widely adopted in coal mines when tunneling in the coal bed. Figure 1(b) shows the local ventilation system of the twin tunnel. The heading faces depend on the fans and ducts for forced ventilation. The blue arrows in figure 1(b) represent the flow direction of the fresh air and the yellow arrows represent the flow direction of polluted air. If the methane outburst occurs at the heading face, the huge momentum carried by the emitted methane will change the flow direction of the underground air. The methane will get into the intake-air tunnel due to the interaction between the methane and air. As mentioned above, there are more workers and equipment in this tunnel. Therefore, explosion and asphyxiation accidents will be more easily caused. Furthermore, if the methane can reach the point A as shown in figure 1(a), the methane will enter the main intake-air tunnels and it will spread all over the mine through the ventilation system, then more serious accidents will be caused. This phenomenon is called the “backward flow” of the methane. To study the relationship between the maximum distance that the methane can flow backward and its influencing factors can help conduct engineering design and take rescue measures after methane outburst.

Many authors have investigated the methane behavior in different tunnels of coal mines. Nakayama et al [4] developed a Computational Fluid Dynamics (CFD) model for methane distribution in mining face. An important finding of Nakayama's study is that the methane concentration was found higher at
location transversely in and along with the corner space where the face end meets the ceiling and the floor as well as the area underneath the ventilation duct. Ichinose et al [5] validated Nakayama's model using experimental results. Torano et al [6] investigated the airflow behavior and methane dispersion in one and two auxiliary ventilation systems by CFD models and validated them by the data from the underground coal mine Carbonara SA located in Northern Spain. They also analyzed the advantages and drawbacks of risk indexes with a greater impact on the prediction and control of the methane outbursts in a heading driven in the underground coal mines of Hullera Vasco Leonesa SA (HVL). Rodriguez et al [7] studied the methane emissions in a tunnel excavated through carboniferous strata based on underground coal mining experience. Fang et al [8] investigated the airflow behavior and methane dispersion near the cross-aisle of a twin-tunnel construction by a three-dimensional CFD model and validated the model by field measurements data. They also obtained the methods to eliminate the “dead zone” in the tunnel. Zhou et al [9] simulated the methane distribution at a continuous mining face with various curtain setback distance based on the CFD model and validated it by the experimental data collected in a full-scale ventilation test facility. Kurnia et al [10] studied the methane dispersion in a mine tunnel with discrete methane sources based on CFD approach and explored the methods to handle the methane in the tunnel. Mishra et al [11] conducted a CFD study on the dispersion of methane in the tailgate of a retreat longwall mine and the simulation results agreed well with the experimental data obtained from a full-scale coal mine. Qin et al [12] investigated the longwall goaf methane flows and borehole drainage performance by CFD simulation. Li et al [13] assessed the hazardous zone in the coal mine tunnel after methane outburst based on CFD method. Lu and Wei [14] adopted a kind of multi-component LBM model to study the gas migration and hindering in the underground tunnel but they didn't apply the turbulent model in the simulation. In general, the studies on the methane behavior in the coal mine tunnel mainly focused on the problems that the methane outburst has not occurred, the backward flow of the methane in the tunnel after methane outburst was rarely investigated. The methods used for investigating the methane behavior in the coal mine tunnel are mainly based on the traditional CFD methods which solving the Navier-Stokes (N-S) equation.

The Lattice Boltzmann Method (LBM) as a potential numerical method has several advantages over the conventional CFD methods [15]. The advantages are mainly embodied in its numerical stability [16] and accuracy [17] and the capacity to efficiently handle complex geometries. Besides, the LBM is an explicit numerical scheme with only local operations. It has the advantage of being easy to implement and is especially well suited for massively parallel machines like graphics processing units (GPUs) [18]. As a consequence of the GPU's architecture, computational speed-up of many orders of magnitude can be achieved in comparison to traditional CPU simulation [19]. In addition, the LBM is widely adopted in the simulation of the coal-bed methane migration, adsorption, and desorption process in a coal seam in recent years [20,21]. Adopting the LBM is convenient for making better use of previous research to simulate the whole process of the methane outburst in the future.

The physical essence of the methane backward flow in coal mine tunnels is the interaction between the methane and underground air under turbulent condition. There are mainly three models to simulate the multi-component gas flow using LBM. They are the passive scalar model, the single collision model, and the split collision model respectively [22,23]. The passive scalar model is the easiest to implement but it can only simulate the effect of one of the components to others. This model is just suitable for the situation that the molar fraction of one of the components is extremely higher than others and the effect of other components can be neglected [24]. The single collision model can simulate the interaction among the components but the viscosity of each component cannot be tuned separately [25]. The split collision model can overcome above shortages [26] and only this model has the capability to simulate the methane backward flow in coal mine tunnels after methane outburst. There are mainly three means to simulate the turbulent flow using LBM. They are Direct Numerical Simulation (DNS) [27], Large Eddy Simulation (LES) [28] and Reynolds Average Navier-Stokes (RANS) [29] respectively. The DNS model is well accepted in Physics because of its exceptional accuracy but the DNS model is uneconomical to simulate the engineering problems because it requires
enormous computational ability [30]. The RANS models offer the most economical approach for computing complex turbulent industrial flows but the RANS models are the time-averaged turbulence models and it cannot give detailed fluctuation of velocities in the turbulent flow simulation. The LES model can give the detailed fluctuation of velocities in the turbulent flow simulation and it requires less computational ability than the DNS model [31].

The LBM coupled with the LES made great progress in recent years and it has been successfully used in the simulation of many complex engineering problems at the macro level. Ren et al [32] designed a GPU-accelerated solver for turbulent flow and scalar transport based on the LBM-LES model. Nathen et al [33] studied the adaptive filtering for the simulation of turbulent flows with LBM-LES model. Premnath et al [34] investigated the dynamic subgrid-scale modeling of turbulent flows using LBM-LES model. Ahmad et al [35] simulated the gust index in an urban area using this method. Cheng et al [36] employed this method to simulate the wind gust structure in the atmospheric boundary layer. King et al [15] studied urban airflow and natural ventilation using this method. Sajjadi et al [37] simulated the indoor airflow and particle dispersion and deposition based on this method. Jacob et al [38] assessed the wind comfort in full-scale city area using this method. Mayer and Hazi [39,40] simulated the longitudinal flow along with the triangular array of rods using this method.

The aim of this research is to introduce and develop the multi-component LBM coupled with LES model that can simulate the backward flow of the methane in the tunnel after methane outburst and study the relationship between the maximum distance that the methane can flow backward in the tunnel after methane outburst and the air velocity, the intensity of the methane outburst, and the width of the tunnel.

2. Lattice Boltzmann model

At the macro level, the methane-air flow can be deemed as Convective-Diffusion phenomenon and the Convection-Diffusion equation [41] can describe it.

\[
\frac{\partial C}{\partial t} = \nabla \cdot (D \nabla C) - \nabla \cdot (C \bar{u})
\]  

(1)

where \(C\) is the volume fraction of methane or air, \(t\) is the time, \(\bar{u}\) is the velocity of mixed gases, \(D\) is the diffusion coefficient between methane and air.

The incompressible Navier-Stokes equation can give the velocity of mixed gases.

\[
\frac{D\bar{u}}{Dt} = F - \frac{1}{\rho} \nabla P + \nu \nabla^2 \bar{u}
\]  

(2)

where \(\rho\) is the density of the mixed gases, \(\nu\) is the kinematic viscosity coefficient, \(F\) is the body force. The coupled solution of incompressible N-S Equation and Convection-Diffusion Equation can calculate the velocity field of the mixed gases and concentration field of various gases. However, the physical essence of the methane backward flow after methane outburst in the coal mine is the collision between methane molecules and air molecules. The macro control equation is challenging to describe the physical essence of the interaction between methane and underground air. LBM as a numerical simulation method based on Statistical Physics, it has rapidly emerged as a powerful technique with great potential for numerically solving momentum, energy, species transport, and multiphase problem.

In this paper, we aim to use LBM to solve the interaction process between the air and methane in the tunnel after methane outburst.

The evolution equation of the split collision Lattice Boltzmann model [42] is

\[
f_a' \left( \vec{r} + c'_a \Delta t, t + \Delta t \right) - f_a' \left( \vec{r}, t \right) = \Omega_a'
\]  

(3)

where \(\vec{r}\) is the spatial position, \(\Delta t\) is the time step, \(f_a'\) is the distribution function of component \(i\),
\( \Omega^i_\alpha \) is the collision term. In two-dimensional case, D2Q9 model [43] is most popular and the \( e^i_\alpha \) is

\[
e^i_\alpha = \begin{cases} 
0 & \alpha = 0 \\
 c^i \left( \cos \left( (i-1) \pi / 2 \right), \sin \left( (i-1) \pi / 2 \right) \right) & \alpha = 1,2,3,4 \\
 \sqrt{2} c^i \left( \cos \left( (i-5) \pi / 2 + \pi / 4 \right), \sin \left( (i-5) \pi / 2 + \pi / 4 \right) \right) & \alpha = 5,6,7,8 
\end{cases}
\] (4)

c^i represents the lattice speed for component \( i \). We adopt the Different Lattice Speed (DLS) [44,45] scheme herein to simulate the fluids consist of the components with different molecular weights. Assuming component 1 is the lightest component and the definition of \( e^i_\alpha \) is

\[
e^i_\alpha = \frac{1}{c^2_{s,i}} \left( e^i - \bar{u} \right) \left( \bar{u}^\text{eq} - \bar{u} \right) \left( 1 + \frac{e^i \cdot \bar{u} \cdot \bar{u}}{c^2_{s,i}} \right) \left( 1 + \frac{\left( e^i \cdot \bar{u} \right)^2}{2 c^4_{s,i}} \right)
\] (7)

with the weights \( \omega_0 = 4/9, \omega_1 = 4/9, \omega_2 = 1/36 \). The relationships between the mass concentration \( \rho_i \) and the equilibrium velocity \( \bar{u}^\text{eq}_i \) of each component and the distribution functions are as follows:

\[
\rho_i = \sum_\alpha f^i_\alpha = \sum_\alpha f^{i,eq}_\alpha
\] (8)

\[
\rho_i \bar{u}^\text{eq}_i = \sum_\alpha e^i_\alpha f^i_\alpha = \sum_\alpha e^{i,eq}_\alpha f^{i,eq}_\alpha
\] (9)

The expressions for the total concentration and the mixture velocity are

\[
\rho = \sum_{i=1}^N \rho_i
\] (10)

\[
\rho \bar{u} = \sum_{i=1}^N \rho_i \bar{u}^\text{eq}_i
\] (11)
\( \Omega_{ij}^{\alpha\beta} \) represents the effect of cross-collisions between different components. Its definition is [26]

\[
\Omega_{ij}^{\alpha\beta} = -\frac{1}{\tau_{ij}} \left( \frac{\rho_{ij}}{\rho} \right) f_{ij}^{eq} \left( e_{ij}^{eq} - \bar{u} \right) \left( \bar{u}_{ij}^{eq} - \bar{u}_{ij} \right)
\]  

(12)

Owing to the large computation domain of the coal mine tunnel, the flow of the methane and air is obvious turbulence and we must introduce the turbulence model. The LBM-LES model means the LBM formation of the standard Smagorinsky model of the Large Eddy Simulation (LES) [46].

Introducing the dimensionless number \( Re \) and \( Sc \) to realize the conversion of the physical unit and lattice unit. Both the \( Re \) and \( Sc \) are constant no matter in the physical system or the lattice system. The definitions of the dimensionless number \( Re \) and \( Sc \) are as follows

\[
Re = \frac{ud}{\nu}, \quad Sc = \frac{\nu}{D}
\]  

(13)

where \( u \) is the characteristic velocity of the methane-air mixture, \( d \) is the width of the tunnel, \( \nu \) is the viscosity of the methane-air mixture, \( D \) is the diffusion coefficient between the methane and air.

3. Full-scale simulation of the methane backward flow after methane outburst

3.1. Object of the full-scale simulation
In order to explore the mechanism and influencing factors of methane backward flow. We select the region in the dotted line frame in figure 1(b) as the object of the simulation. Figure 2 shows the physical dimensions and boundary conditions of the simulation. The tunnel is 200 m long, 5 m wide and 3 m high. Assuming that the methane outburst will destroy the air ducts. The inlet of the tunnel applies the air velocity boundary, the outlet of the cross-aisle applies the fully developed boundary, the wall of the tunnel applies the bounce back boundary, the heading face applies the methane velocity boundary during methane outburst and the bounce back boundary before and after methane outburst.

![Figure 2. Boundary conditions of the simulation.](image)

We tested three kinds of grid resolution and they were 0.25 m/dx, 0.5 m/dx and 1 m/dx respectively. Three kinds of grid resolution obtained the approximate simulated results. Considering the computing time, this paper adopts the grid resolution of 0.5 m/dx.

3.2. Result and discussion
Figure 3 shows the initial air flow state in the air-intake tunnel before methane outburst (the 50s) when the inlet-velocity is 1 m/s. Figure 4 shows the methane concentration field at different evolution time when the intensity of the methane outburst is 150 m³/s and the inlet-velocity is 0.5 m/s. As we can see, during the methane outburst (50s-70s), the methane can flow both along and against the initial air
flow. The distance that the methane flow backward increases with the evolution time, but the increasing rate slows down gradually. When the methane outburst ends (the 70s), the distance that the methane flow backward reaches the maximum and the fresh air from the inlet of the air-intake tunnel will eliminate the methane which flows back into the tunnel. It is important to note that the elimination rate of methane in the blind tunnel is very low. The methane with high concentration is easily accumulated in the blind tunnel for a long time. It can explain why the workers are strictly forbidden to enter the blind tunnel in the underground coal mine.

Figure 3. Initial air flow state.

Figure 4. Methane behaviour after methane outburst.

Studying the influence factors of the maximum distance that the methane can flow against the
initial air flow is critical to help conduct engineering design and take safety measures. The influences of the intensity of the methane outburst, the initial air velocity and the width of the tunnel to the maximum distance that the methane can flow against the initial air flow are discussed in this part. In order to quantitatively describe the maximum distance that the methane can flow against the initial air flow, we define the distance $L_m$ from the heading face to the farthest cross-section that the average methane concentration is larger than 1% as the maximum distance that the methane can flow backward.

Figure 5 shows the different $L_m$ when the inlet air velocities are 0.25-2 m/s and the intensity of the methane outburst is 150 m$^3$/s. It demonstrates that the distance $L_m$ decreases with the increase of the inlet air velocities and they show a good linear relationship. The fitting formula and the R-square are shown in figure 5. We can conclude from the fitting formula that increasing the inlet air velocity by 1 m/s can reduce the distance $L_m$ by 26 m when the intensity of the methane outburst is 150 m$^3$/s. Increasing the inlet air velocity in the air-intake tunnel can reduce the influence range of methane outburst effectively.

![Figure 5](image)

**Figure 5.** The $L_m$ at different inlet air velocities.

Figure 6 shows the different $L_m$ when the intensity of the methane outburst are 75-180 m$^3$/s and the inlet air velocity in the air-intake tunnel is 0.5 m/s. It demonstrates that the distance $L_m$ increases with the increase of the intensity of the methane outburst and there exists the linear relationship between them. Figure 6 shows the fitting formula and the R-square.

![Figure 6](image)

**Figure 6.** The $L_m$ at different intensities of methane outburst.

Figure 7 shows the different $L_m$ when the width of the tunnel is 3-6 m when the intensity of the methane outburst is 90 m$^3$/s. It demonstrates that the distance $L_m$ are basically stable at 70 m and it shows a small range of fluctuations with the change of the tunnel width. It demonstrates that the change of the tunnel width has almost no effect on the distance $L_m$ (The proportion of each tunnel...
remains unchanged).

\[ Figure \text{ 7.} \text{ The } L_m \text{ at different tunnel width.} \]

4. Conclusion
The introduced LBM model coupled with the LES model can simulate the methane backward flow in coal tunnels after methane outburst.

With the increase of the inlet air velocity, the distance that the methane can flow backward decreases. There exists a linear relationship between the inlet air velocity and the distance that the methane can flow backward. Increasing the tunnel air velocity can reduce the maximum distance that the methane can flow backward after methane outburst obviously. The tunnel air velocity should be increased as much as possible when the economic and other conditions are met in practice.

With the increase of the intensity of the methane outburst, the distance that the methane can flow backward increases. There exists a linear relationship between the intensity of the methane outburst and the distance that the methane can flow backward. This relation can help calculate the intensity of the methane outburst which cannot be obtained through the measuring equipment owing to the instantaneity, uncertainty, and destructiveness of the methane outburst in practice.

The change of the tunnel width (The proportion of each tunnel remains unchanged.) has almost no influence on the distance that the methane can flow backward. The maximum distance that the methane can flow backward should not be considered when determining the width of the tunnel in practice. The width of the tunnel should be small as much as possible to reduce the cost.

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