

## Article

# Research on Optimization of Sealing Process and Explosion Hazard of Railway Auxiliary Tunnels Containing Methane

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## Abstract

To ensure the safe operation of railway tunnels and prevent methane disasters in auxiliary tunnels, this paper focuses on the post-construction closure of an auxiliary tunnel (cross tunnel) in a railway tunnel with methane presence. Computational Fluid Dynamics (CFD) simulations were employed to investigate methane migration and accumulation patterns under different sealing conditions in railway auxiliary tunnels. The optimal auxiliary tunnel end-face closure method was identified. Subsequently, the influences of factors such as tunnel length and methane concentration on the explosion characteristics were analyzed under the optimal closed process conditions. The results show that after methane escapes from the coal seam, it initially accumulates at the tunnel's roof and then diffuses downward due to the concentration gradient. When the lower end face of the auxiliary tunnel is opened and the upper end face is sealed, the degree of methane enrichment in the tunnel is the lowest and the enrichment speed is the slowest. Under partial methane conditions, the explosion pressure propagated and released more easily within the tunnel, leading to higher peak pressure. As the length of the tunnel increases, the peak pressure of the explosion increases, and the explosion power becomes greater. The overpressure of the explosion shock wave follows a nonlinear relationship with distance and is inversely proportional to the square root of the distance. The findings provide theoretical guidance for the prevention and control of methane-related accidents and disasters.

**Keywords:** auxiliary tunnels; methane migration law; methane explosion; numerical simulation; methane emission



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## 1. Introduction

Railway transportation, as an important component of transportation infrastructure, plays a crucial role in alleviating transportation pressure. Over the past two decades, China has seen rapid development in railway tunnel construction, with a growing number of tunnels built in complex geological conditions [1,2]. However, during tunnel construction through coal seams, harmful gases such as methane may accumulate. The encounter of methane with an ignition source can lead to explosions, posing a serious threat to construction safety [3–6]. Therefore, studying methane accumulation and explosion patterns in tunnels, especially the propagation of shock waves during explosions, is of great significance.

The main cause of methane accidents is excessive methane accumulation. During tunnel construction through coal seams, studying the methane enrichment and diffusion patterns can effectively prevent methane disasters. The diffusion of methane is influenced by the coupling of multiple factors, including the gas flow field, coal stress field, and

temperature field inside the coal seam [7]. When the temperature of the methane and coal is kept constant, the effective permeability of the methane decreases as the moisture content of the coal seam increases [8]. Liu et al. [9] studied the diffusion patterns of harmful gases in tunnel construction in plateau regions and optimized ventilation conditions. Liao et al. [10] used FLACS software to analyze the leakage and diffusion characteristics of natural methane in tunnels under different operational scenarios. Regarding tunnel methane disasters, Li et al. [11] predicted short-term methane concentration trends for each construction step of the excavation face by analyzing the time series of tunnel methane concentrations. Zhang et al. [12] established a methane risk assessment system for non-coal tunnel methane outbursts based on attribute mathematics during the tunnel survey phase.

An increase in methane concentration inside tunnels raises the risk of methane explosions. To effectively prevent methane accidents, it is necessary to study the explosion patterns of methane in the internal space of tunnels. A considerable amount of research has been conducted on the propagation patterns of methane explosion shock waves [13–18]. Due to the instability of the flow field in tunnels, Jiang et al. [19] explored the impact of turbulence intensity ( $u_0$ ) on the flame propagation characteristics and extinguishing limits of methane/coal dust explosions. Su et al. [20] found that, under non-venting conditions, the explosion pressure and temperature of methane in pipelines are highest; these decrease sequentially in pipelines with end-point ignition and venting, and in pipelines with same-point ignition and venting. Zhang et al. [21] established an explosion ventilation system to study the impact factors of venting position in single-container explosions. Huang et al. [22] used FULENT software to explore the flame and pressure wave propagation patterns in pipeline methane explosions, and Bao et al. [23] studied the impact of methane concentration and ventilation pressure on the transient overpressure of indoor methane explosions. Additionally, research on tunnel explosions has highlighted the significant dangers posed by these confined structures [24]. Zhu et al. [25] studied the characteristics of methane-air explosions in large tunnels with different structures, finding that flames tend to propagate towards free space, and larger volumes of combustible mixtures result in flames that fill longer tunnels more thoroughly. Gao et al. [26] studied the propagation of overpressure during excavation methane explosions, finding that the overpressure curve rises and falls over time before stabilizing, with venting chambers and explosion-proof walls providing certain venting effects. Li et al. [27] tested the propagation of explosions in tunnels of various volumes and found that explosion pressure does not decay linearly with distance but fluctuates along the tunnel. Throughout the explosion, the flame propagation speed increases and then decreases. Liu et al. [28] found that, under certain conditions, the maximum explosion overpressure inside the tunnel follows a parabolic trend as the blockage ratio increases due to the accumulation of rubble. Zhang et al. [29] found that obstacles can enhance the turbulent combustion of explosion flames, increasing instability and causing certain levels of damage to tunnel structures. Methane explosions in mines cause significant damage to tunnels, with the shock load from methane explosions first loading onto the closed end wall, resulting in wall deformation and equivalent stress [30]. Furthermore, researchers have studied the impact of ignition location [31], initial pressure [32,33], and other factors on methane explosions. Therefore, understanding the explosion pressure patterns and structural responses of methane in confined spaces can help effectively predict and prevent tunnel explosion accidents.

Although many scholars have studied methane diffusion and explosion problems inside tunnels using theoretical, experimental, and numerical simulation methods, most research focuses on the tunnel excavation phase. There is limited research on the methane accumulation and explosion characteristics within auxiliary tunnels after completion. Therefore, this study investigates the methane enrichment behavior in auxiliary tunnels under

different tunnel end-face closure conditions, aiming to identify the optimal auxiliary tunnel end-face closure method. Furthermore, under the optimal tunnel end-face closure method, the influence of methane concentration and tunnel length on the explosion hazard of methane was studied.

## 2. Research Methods

### 2.1. Basic Assumptions for Numerical Simulation

- (1) In the study of methane diffusion and enrichment, the fluid within the auxiliary tunnel is treated as being composed of continuously distributed mass points, meaning there are no gaps between fluid particles, and methane flow conforms to the continuity equation.
- (2) The methane within the auxiliary tunnel is regarded as an incompressible fluid, and variations in fluid density are neglected.
- (3) The flow field within the auxiliary tunnel is considered an isothermal flow field. The methane flow in the tunnel is treated as a steady turbulent flow with constant temperature, and there is no heat exchange between the methane and the tunnel walls during the flow process.
- (4) The methane in the auxiliary tunnel is assumed to consist solely of methane and air. The coal seam is the only source of methane emission, and the methane is uniformly exuding into the auxiliary tunnel.
- (5) To simplify the calculations, the intermediate products of methane explosion are ignored, leaving only the methane explosion heat source. The air pressure in the auxiliary tunnel is assumed to be atmospheric pressure, and the lining walls are considered smooth and adiabatic.

### 2.2. Methane Diffusion Governing Equation

The standard k- $\epsilon$  bidirectional turbulence model was adopted for simulation, and the main control equations are as follows [34]:

- (1) Continuity equation

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{V}) = 0 \quad (1)$$

where  $\rho$  is the gas density, with the unit of  $\text{kg}/\text{m}^3$ ;  $\mathbf{V}$  is the velocity vector.

- (2) Equation of conservation of momentum

$$\frac{\partial}{\partial t}(\rho \mathbf{V}) + \nabla \cdot (\rho \mathbf{V} \mathbf{V}) = -\nabla p + f_v + \nabla \cdot \tau \quad (2)$$

where  $p$  denotes the gas pressure, Pa;  $f_v$  represents the volume force source term per unit volume acting on the fluid, N;  $\tau$  stands for the stress tensor.

- (3) Energy conservation equation

$$\frac{\partial(\rho T)}{\partial t} + \nabla \cdot (\rho T \mathbf{V}) = \nabla \cdot \left( \frac{K}{c_p} \nabla T \right) + S_T \quad (3)$$

where  $T$  denotes the temperature inside the tunnel, K;  $c_p$  denotes the specific heat capacity, J/(kg·K);  $K$  represents the gas heat transfer coefficient, W/(m<sup>2</sup>·K);  $S_T$  stands for the viscous work term.

- (4) Component mass conservation equation

$$\frac{\partial(\rho c_s)}{\partial t} + \nabla \cdot (\rho c_s \mathbf{V}) = \nabla \cdot [D_s \nabla(\rho c_s)] + S_l \quad (4)$$

where  $c_s$  denotes the mass concentration fraction of the component;  $D_s$  represents the diffusion coefficient of the component;  $S_l$  stands for the generation rate of each component per unit volume.

(5) k- $\varepsilon$  Equation

$$\begin{cases} \nabla \cdot (\rho \mathbf{V} k) = \nabla \cdot \left( \mu + \frac{\mu_t}{\sigma_k} \nabla k \right) + G - \rho \varepsilon \\ \nabla \cdot (\rho \mathbf{V} \varepsilon) = \nabla \cdot \left( \mu + \frac{\mu_t}{\sigma_\varepsilon} \nabla \varepsilon \right) + (c_1 G - c_2 \rho \varepsilon) \frac{\varepsilon}{k} \\ G = \mu_t \left( \frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i} \right) \frac{\partial v_i}{\partial x_i} \\ \mu_t = \frac{c_\mu \rho k^2}{\varepsilon} \end{cases} \quad (5)$$

where  $k$  denotes the turbulent kinetic energy,  $\text{m}^2/\text{s}^2$ ;  $\varepsilon$  represents the turbulent energy dissipation rate,  $\text{m}^2/\text{s}^3$ ;  $\mu$  and  $\mu_t$  denote the dynamic viscosity coefficients of laminar flow and turbulent flow, respectively,  $\text{Pa}\cdot\text{s}$ ;  $G$  stands for the turbulent energy generation rate;  $c_1$ ,  $c_2$ ,  $c_\mu$ ,  $\sigma_k$  and  $\sigma_\varepsilon$  are coefficients.

### 2.3. Methane Explosion Control Equation and Overpressure Attenuation Equation

Tunnel methane explosion is the process in which shock waves propagate in a confined space. In the Cartesian coordinate system, the following conservation laws and equations [35] are satisfied:

Equation of conservation of mass:

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} + \frac{\partial(\rho w)}{\partial z} = 0 \quad (6)$$

Equation of conservation of momentum:

$$\begin{cases} \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} = -\frac{1}{\rho} \frac{\partial p}{\partial x} \\ \frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} = -\frac{1}{\rho} \frac{\partial p}{\partial y} \\ \frac{\partial w}{\partial t} + u \frac{\partial w}{\partial x} + v \frac{\partial w}{\partial y} + w \frac{\partial w}{\partial z} = -\frac{1}{\rho} \frac{\partial p}{\partial z} \end{cases} \quad (7)$$

Energy conservation equation:

$$\frac{\partial e}{\partial t} + u \frac{\partial e}{\partial x} + v \frac{\partial e}{\partial y} + w \frac{\partial e}{\partial z} = 0 \quad (8)$$

State equation:

$$p = p(\rho, T) = \rho R T \quad (9)$$

where  $\rho$  denotes the fluid density,  $\text{kg}/\text{m}^3$ ;  $p$  represents the gas pressure,  $\text{Pa}$ ;  $u$ ,  $v$ , and  $w$  denote the velocity components in the  $x$ ,  $y$ , and  $z$  directions, respectively,  $\text{m}/\text{s}$ ;  $t$  stands for time;  $T$  denotes the temperature,  $\text{K}$ ;  $R$  represents the gas constant;  $e$  stands for the specific energy in  $\text{kJ}/\text{kg}$ .

The equation of shock wave overpressure attenuation with distance is

$$\Delta p = \frac{4k}{(k+1)c_0} \sqrt{\frac{E_g(k-1)(k+1)}{s\rho_0(3k-1)}} x^{-0.5} \quad (10)$$

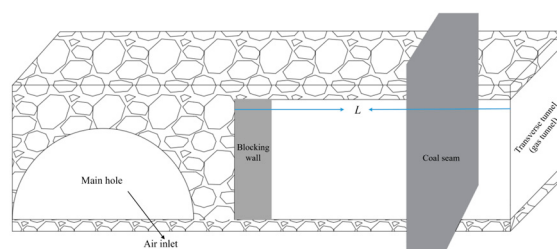
The simplification of Equation (10) yields

$$\Delta p = Bx^{-0.5} \quad (11)$$

## 2.4. Physical Models

### 2.4.1. Simulated Background

Referring to Figure 1, the numerical simulation focuses on the methane diffusion and methane explosion within an auxiliary tunnel that crosses through a coal seam. In this setup, the main tunnel is a railway tunnel that is operational and open for normal traffic, while the auxiliary tunnel (referred to as the cross tunnel) is constructed perpendicular to the main tunnel to support its operation. The auxiliary tunnel has already been excavated and completed. At the connection point between the auxiliary tunnel and the main tunnel, blocking walls have been constructed and sealed to ensure isolation. The upper face of the auxiliary tunnel is open to an external air domain. Three specific scenarios are investigated: (1) the lower face is sealed, while the upper face is open (model 1); (2) the lower face is open, while the upper face is sealed (model 2); (3) both the lower and upper faces are sealed (model 3). Figure 2 shows the schematic diagrams of three working conditions.



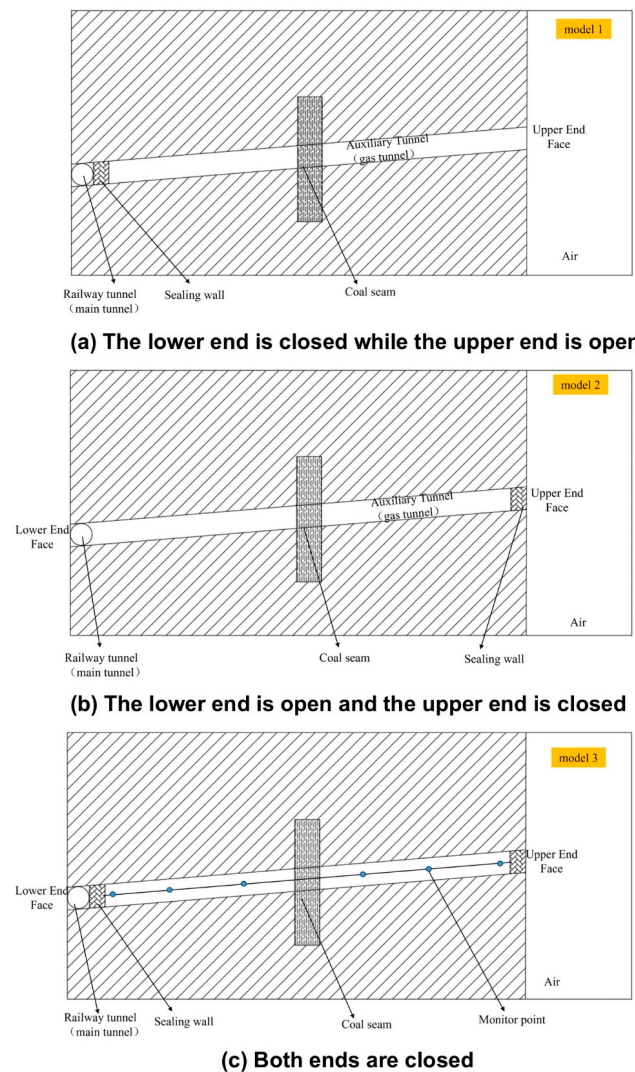
**Figure 1.** Schematic diagram of the simulated background.

### 2.4.2. Simplify the Model and Boundary Names

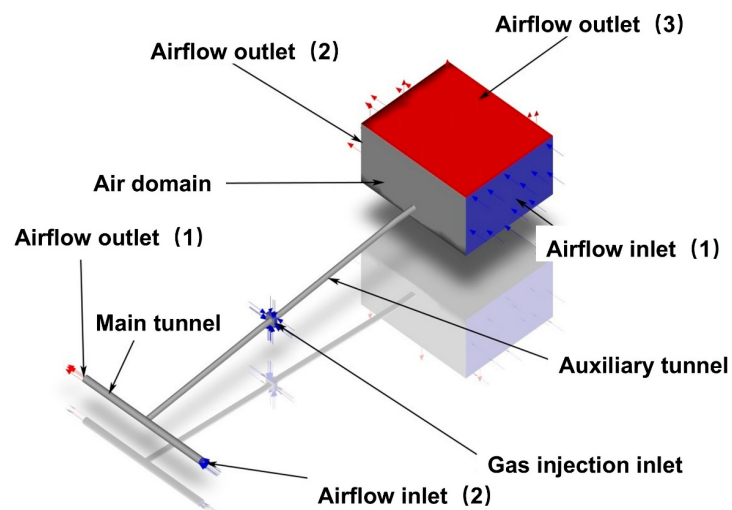
Figure 3 shows a simplified model of the numerical simulation. The model is mainly composed of main tunnel, auxiliary tunnel and air domain. There are Airflow outlet (1) and Airflow inlet (2) at both ends of the main tunnel. Methane is injected from the middle of the auxiliary tunnel. The air domain contains two airflow outlets and one airflow inlet.

### 2.4.3. Grid Independence Test

The grid was gradually refined through local and global refinement methods. During the grid refinement process, the expansion ratio of grid cells was maintained at approximately 1.5. Ultimately, four grid resolutions were generated. The grids were labeled Grid I–IV with cell counts of 752,637, 1,127,911, 1,694,531, and 2,541,322, respectively. Based on Model 2, the explosion situation of partially premixed methane (methane filling half of the roadway and the methane filling concentration is set at 9.5%.) in the roadway was taken as the standard for the grid independence test. The tunnel is 500 m long. Five pressure monitoring points were set up. Monitoring points 1–5 were located at distances of 500 m, 400 m, 300 m, 200 m and 100 m from the ignition point. Figure 4 shows that Grids I and II exhibit significant deviations from Grid IV, while Grid III results closely match those of Grid IV. Considering both computational accuracy and cost, Grid III was selected as the optimal grid for this study.



**Figure 2.** Schematic diagrams of the three working conditions.



**Figure 3.** Simplified model of the numerical simulation.

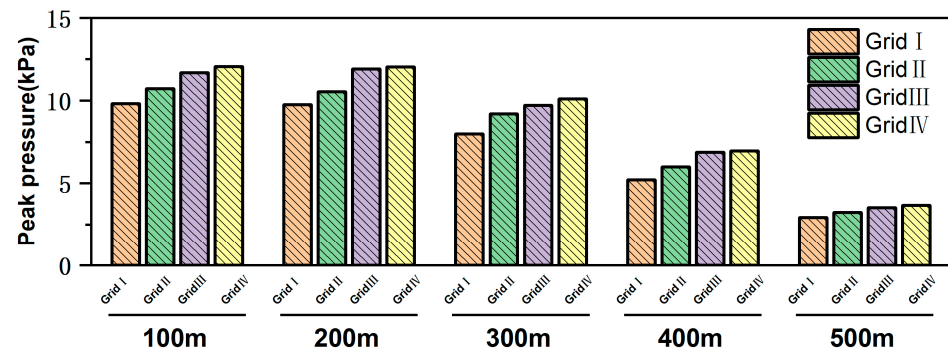


Figure 4. Comparison between experimental data and simulated data.

### 2.5. Model Parameters and Boundary Conditions

- (1) Methane Diffusion Simulation Parameters and Boundary Conditions: Based on the research objectives, experimental conditions, and existing theoretical knowledge, the flow velocity of methane entering through the coal seam is set to  $2.78 \times 10^{-6}$  m/s. Given that the spreading area of methane inflow is  $300 \text{ m}^2$ , the volumetric flow rate is converted to  $0.05 \text{ m}^3/\text{min}$ . The right side of the air domain is set as an air inlet with a velocity of  $0.001 \text{ m/s}$ . The thickness of the coal seam intersected by the auxiliary tunnel is  $5 \text{ m}$ , with no other methane sources present. The gravitational acceleration in the Y-direction of the model is set to  $-9.8 \text{ m/s}^2$ . The fluid domain is entirely filled with air at a temperature of  $300 \text{ K}$ . The tunnel's inner walls are modeled with standard roughness, as the inner walls have been reinforced with secondary lining, and the roughness coefficient is taken as  $0.05$ .
- (2) Methane Explosion Simulation Parameters and Boundary Conditions: The explosion simulation is carried out using Standard k- $\epsilon$ . The left end of the tunnel is sealed, while the right end is open and set as a pressure outlet with a gauge pressure of  $0 \text{ Pa}$ . A circular region with a radius of  $1 \text{ m}$  is created near the left end face, where ignition and detonation are initiated. The combustion model is set to partially premixed combustion, with the premixing model defined by the C equation and the flame model set to "steady diffusive small flame". The GRI Mech 3.0 combustion mechanism is selected for the simulation.

### 2.6. Similarity Experiment

Similar experiments were conducted to verify the reliability and accuracy of the simulated data. Figure 5 shows a similar experimental platform. The experimental setup primarily comprises a simulated tunnel, helium concentration sensor, a premixed gas storage tank, and gas injection ports. The scaling ratio between the experimental platform and the numerical simulation geometric model is 1:20. Given safety concerns associated with methane's explosiveness, helium was substituted for the experiments. A mixture of helium and air was prepared, and its density was adjusted to match that of methane. The mixed gas was injected into the simulated roadway through an injection port, and its concentration was measured by a helium concentration sensor. Meanwhile, in the numerical simulation, a mixture of helium and air with the same composition was also injected. In the numerical simulation, the volumetric flow rate of the mixed gas is  $0.05 \text{ m}^3/\text{min}$ . In similar experiments, the injection volume is determined based on the scaling ratio. Finally, under Model 1 (The lower face is sealed, while the upper face is open), similar experiments and numerical simulations were conducted. Due to the limitations of laboratory conditions, this study only monitored the helium concentration values in the upper section of similar roadways.

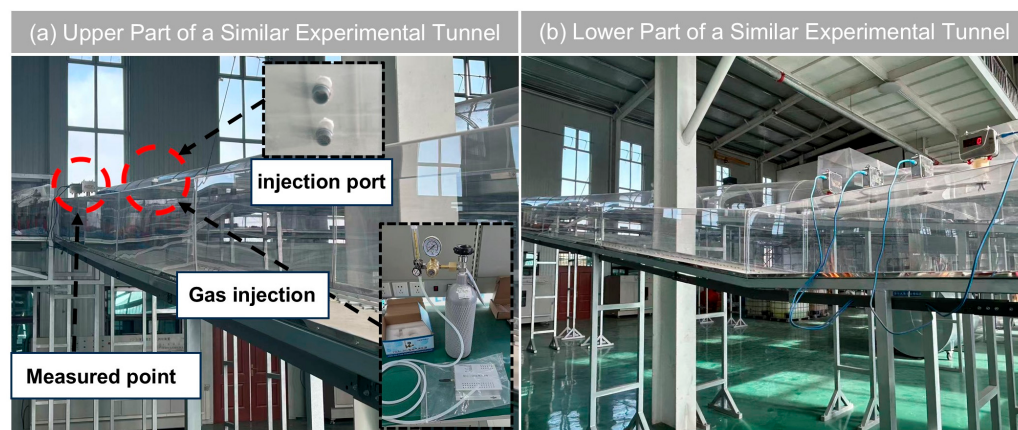


Figure 5. Similar experiment platform: (a) upper part of tunnel; (b) lower part of tunnel.

Figure 6 shows the concentration values measured by similar experiments and those monitored in the numerical simulation. The relative error between similar experiments and numerical simulation data ranges from 3.65% to 12.17%, with the majority of cases below 10%. This indicates that the numerical simulation results can explain the actual situation. At the same time, it can be reasonably deduced that the numerical simulation results remain accurate when the mixed gas is replaced with methane.

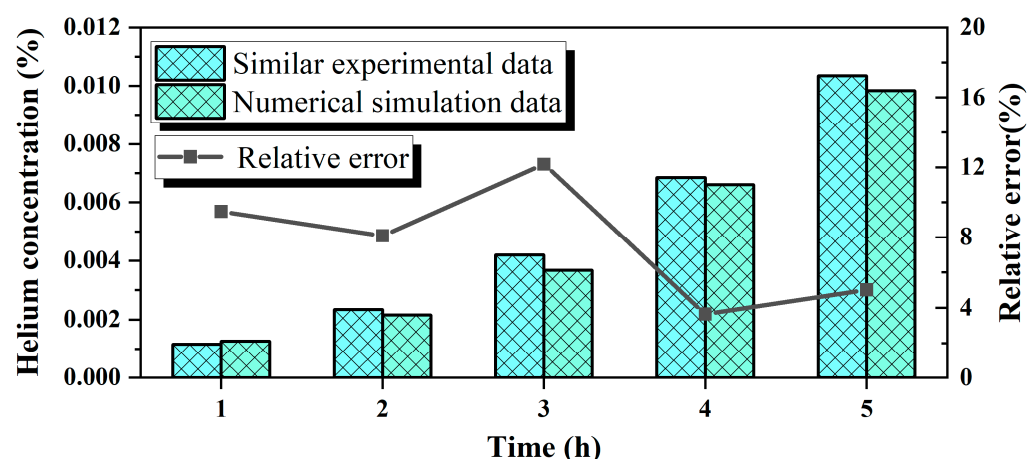
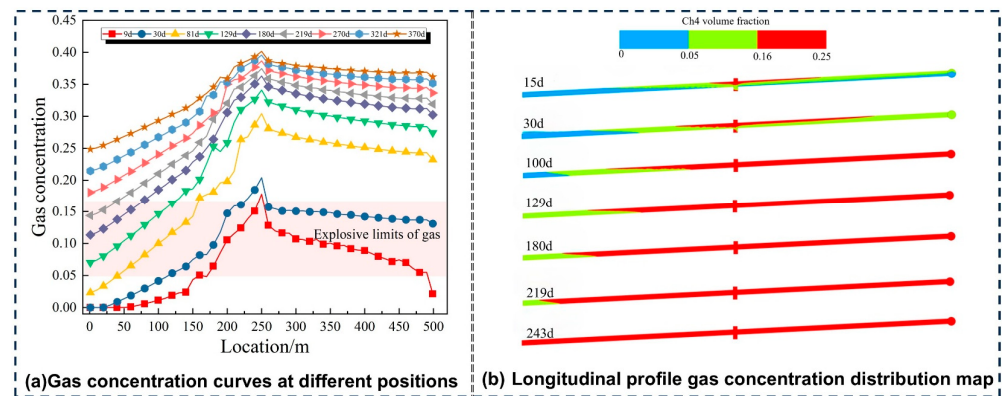


Figure 6. The relative error between numerical simulation and similar experimental data.

### 3. Simulation Results and Analysis

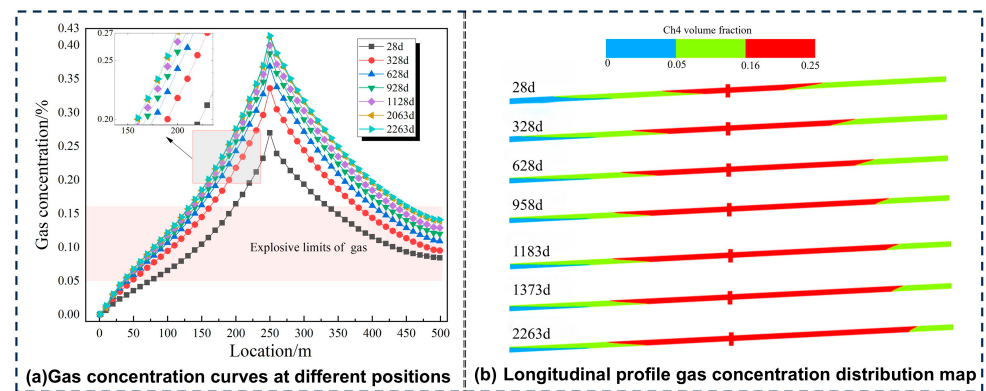
#### 3.1. The Law of Methane Enrichment

Figure 7 shows the methane concentration data and distribution map of Model 1. Figure 7a showed that the methane concentration inside the horizontal tunnel gradually increased over time. The methane concentration in the downhill section was generally lower than that in the uphill section. After 270 days, the methane concentration throughout the tunnel exceeded the explosion limit. The methane concentration distribution map of the horizontal tunnel's longitudinal section is shown in Figure 7b. It can be seen that the methane concentration near the coal seam is consistently higher than in other areas, and within 243 days, the methane concentration in the tunnel rises rapidly. Even when the upper end is completely open, the methane cannot effectively diffuse out, and after 100 days, there is no blue safety zone inside the tunnel. Therefore, opening the upper end did not effectively prevent the accumulation of methane.



**Figure 7.** Methane concentration profile of model 1: (a) methane concentration curves; (b) methane concentration distribution map.

Figure 8 shows the methane concentration data and distribution map of Model 2. From Figure 8a, it can be seen that the methane concentration within the horizontal tunnel followed a pattern where the concentration was highest near the coal seam and gradually decreased toward both ends of the tunnel. On day 28, the methane concentration in the 100 m to 500 m region of the tunnel had already reached the explosion limit. Over time, the methane concentration in this region continued to rise, but the rate of increase gradually decreased. After 928 days, the methane diffusion in the tunnel reached a balanced state, with the methane concentration remaining almost unchanged. Eventually, except for the area near the coal seam, where the methane concentration remained above the explosion limit, the methane concentration in other areas of the tunnel fell within the explosion limit range.

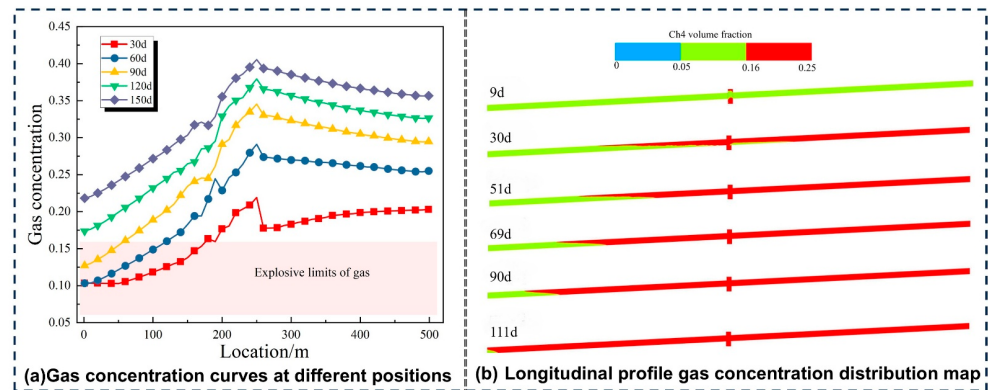


**Figure 8.** Methane concentration map of model 2: (a) methane concentration curves; (b) methane concentration distribution map.

As shown in the methane concentration distribution map of the horizontal tunnel's longitudinal section (Figure 8b), the methane concentration was relatively low in the area close to the lower end face. This is because the unsealed lower end face, which connected to the main tunnel, led some methane to diffuse into the air after spilling out from the coal seam. The lower part near the lower end face remained within the blue safety zone. Due to the proximity to the coal seam, the methane concentration in the central section of the tunnel remained consistently high. As the upper end face was sealed, the methane could not be discharged and the methane concentration remained at a relatively high level.

Figure 9 shows the methane concentration data and distribution map of Model 3. From Figure 9a, it can be seen that, under the condition where both ends are sealed, the methane concentration in the horizontal tunnel reached the explosion limit on day 30 and

remained above it after day 60. Additionally, the methane concentration on the downhill side was generally lower than that on the uphill side. Compared to the other two sealing conditions, under the two-end sealing condition, the overall methane concentration level inside the horizontal tunnel was higher within 150 days.



**Figure 9.** Methane concentration profile of model 3: (a) methane concentration curves; (b) methane concentration distribution map.

The methane concentration distribution map for the vertical profile of the horizontal tunnel (Figure 9b) shows that after the methane spills out from the coal seam, it first gathers at the top. Under the influence of the concentration gradient, the methane diffused uniformly both uphill and downhill, with the diffusion rate being higher on the uphill side than on the downhill side. Within a short period, the methane concentration inside the horizontal tunnel exceeded the explosion limit range. In this condition, there was no blue safety zone inside the tunnel.

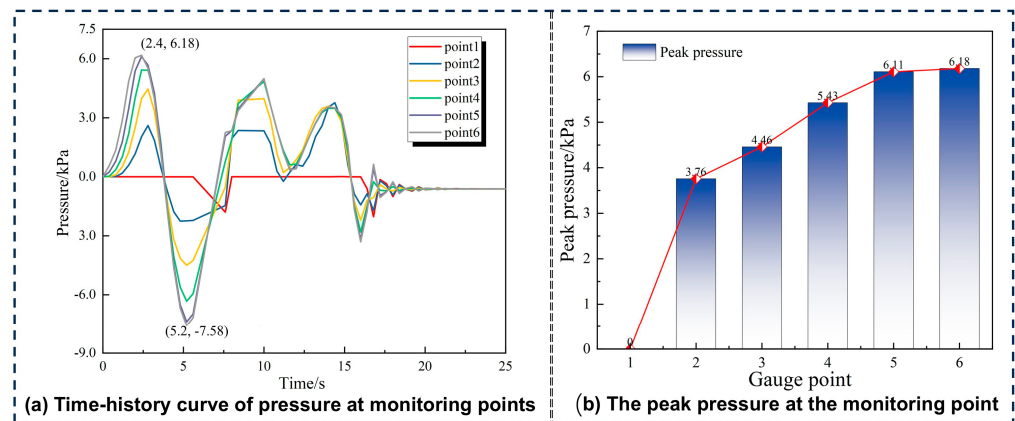
The diffusion and accumulation of methane under three different closed conditions can be summarized as follows: After the methane was emitted from the coal seam, it first accumulated in the uphill section of the tunnel. Then, driven by the concentration gradient, the methane diffused downward. Ultimately, the overall methane concentration in the uphill section was higher than that in the downhill section. Additionally, the methane concentration was highest near the coal seam. The methane concentration distribution in the tunnel's cross-section at different positions followed a “higher at the top, lower at the bottom” pattern, where the concentration decreased from the tunnel crown to the floor, accompanied by a stratification phenomenon.

### 3.2. The Law of Pressure Propagation in Methane Explosion

#### 3.2.1. The Influence of Methane Concentration on the Pressure of Methane Explosion

Based on Model 2, the explosions of fully premixed methane (the tunnel was filled with methane) and partially premixed methane (methane filled half of the roadway) in the roadway were simulated. The methane filling concentration was set to 9.5%. Monitoring points 1–6 were located at distances of 500 m, 400 m, 300 m, 200 m, 100 m, and 0 m from the ignition point.

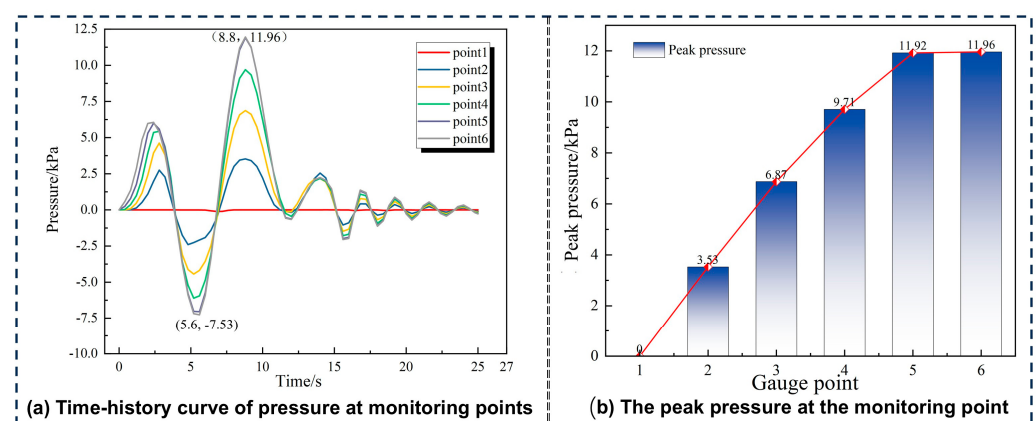
As shown in Figure 10a, when the tunnel was filled with premixed methane, the pressure variations at different monitoring points were relatively consistent. In the early stages of the explosion, the pressure inside the tunnel rose rapidly, reaching a peak value of 6.18 kPa at 2.4 s. Subsequently, the pressure dropped sharply and became negative, reaching its lowest value of −7.58 kPa at 5.2 s. As the explosion progressed, the pressure fluctuations became more pronounced, indicating that the flow field inside the tunnel had become highly turbulent. Finally, the pressure at all monitoring points tended toward zero, signifying the end of the explosion process.



**Figure 10.** Pressure variation at monitoring points under full methane condition: (a) time–history curve of pressure; (b) the peak pressure.

From the pressure peak bar chart in Figure 10b, it could be seen that the pressure peak differences between the monitoring points were minimal, indicating consistent structural response of the tunnel to dynamic loads. The pressure peak values at the monitoring points followed the order: point6 > point5 > point4 > point3 > point2 > point1. This was due to the pressure relief effect at the right-end exit of the tunnel, while the left-end closure caused pressure accumulation. Therefore, the peak pressure decreased as the monitoring point approached the tunnel exit.

Figure 11 shows the explosion pressure curve for the left half of the tunnel filled with methane. In Figure 11, the pressure variation pattern for partially premixed methane in the tunnel was generally similar to that for fully premixed methane, but the peak pressure was higher, and the fluctuations were more frequent, indicating a more complex explosion reaction under partial methane conditions. In the fully premixed methane case, the combustion reaction was limited by insufficient oxygen supply, reducing energy release and resulting in lower peak pressure. In contrast, under partial methane conditions, the explosion pressure propagated and released more easily within the tunnel, leading to higher peak pressure.



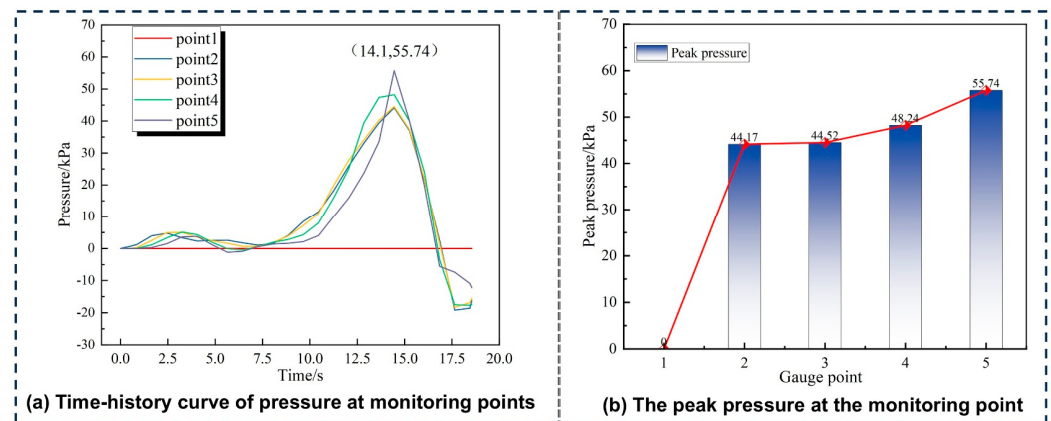
**Figure 11.** Pressure variation at monitoring points under partial methane conditions: (a) time–history curve of pressure; (b) the peak pressure.

### 3.2.2. The Influence of the Length of the Transverse Hole on the Pressure of Methane Explosion

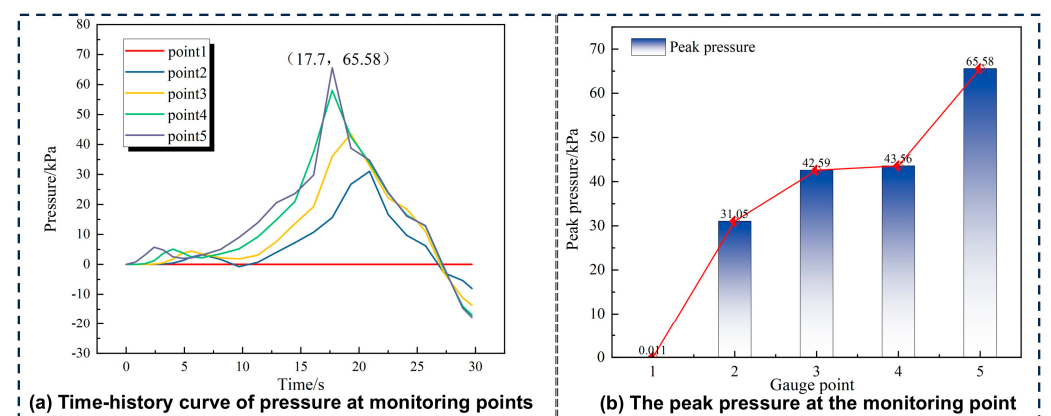
To thoroughly investigate the pressure propagation characteristics of methane explosions in transverse tunnels of varying sizes, three tunnel models with lengths of 1 km, 2 km and 3 km, respectively, were established. Simulation was carried out under partially

premixed methane conditions. Pressure monitoring points were uniformly distributed within the tunnels, extending from the detonation point toward the tunnel exit. In a one-kilometer-long tunnel, monitoring points 1 to 5 are positioned at distances of 1000 m, 750 m, 500 m, 250 m, and 0 m from the detonation point, respectively. In a two-kilometer-long tunnel, monitoring points 1 to 5 are positioned at distances of 2000 m, 1500 m, 1000 m, 500 m, and 0 m from the detonation point, respectively. In a three-kilometer-long tunnel, monitoring points 1 to 7 are located at 3000 m, 2500 m, 2000 m, 1500 m, 1000 m, 500 m, and 0 m, respectively. Upon completion of the simulation, pressure-time curves for each monitoring point were generated.

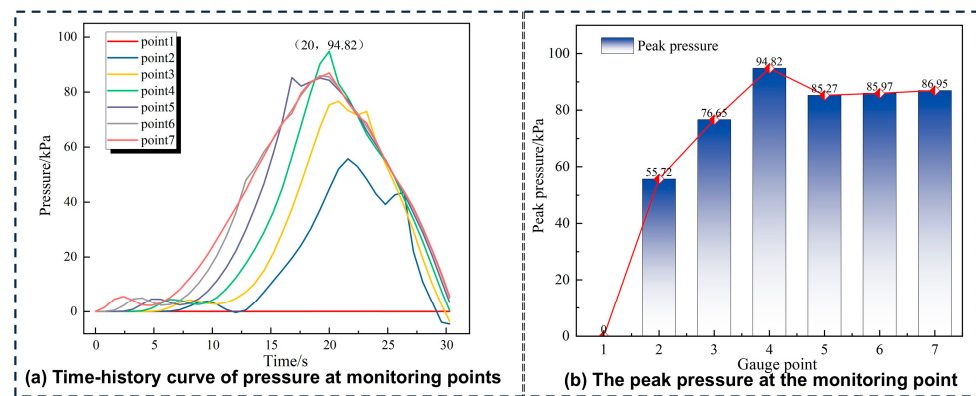
Within the transverse tunnel, the shock wave produced by the explosion undergoes multiple reflections during propagation, resulting in a stepwise increase in pressure at the monitoring points. As shown in Figures 12a, 13a and 14a, during the initial phase of the explosion, pressure variations were relatively minor and accompanied by fluctuations, primarily attributable to the reflection of the shock wave within the tunnel. The closer a monitoring point was to the detonation point, the more pronounced the pressure fluctuations. Over time, the pressure at each monitoring point progressively increased, reaching a peak before sharply declining, with lower pressure values observed at points farther from the detonation point.



**Figure 12.** Pressure variation at monitoring points in a 1000 m tunnel with full methane condition: (a) time–history curve of pressure; (b) the peak pressure.



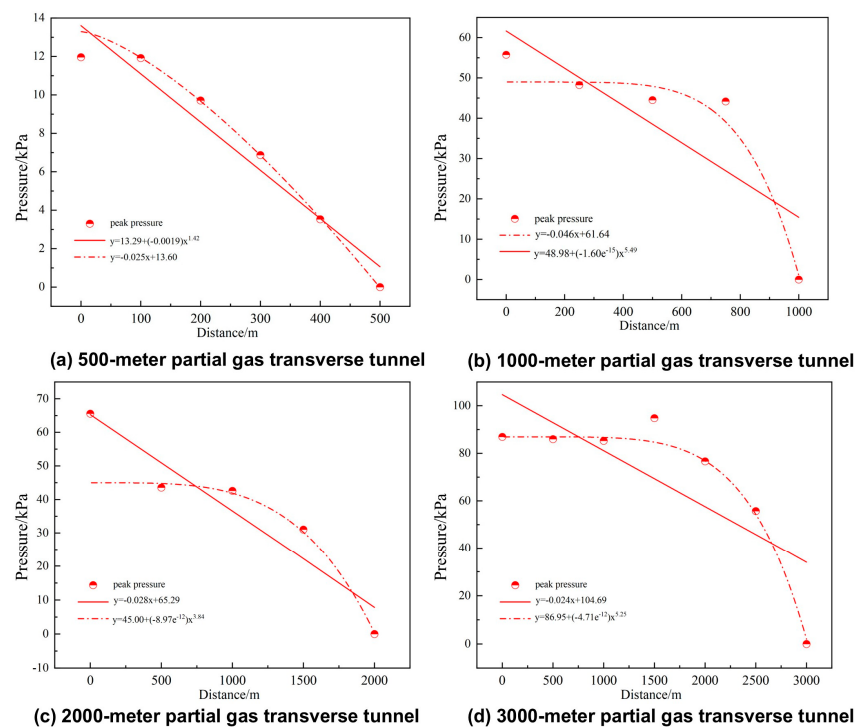
**Figure 13.** Pressure variation at monitoring points in a 2000 m tunnel with full methane condition: (a) time–history curve of pressure; (b) the peak pressure.



**Figure 14.** Pressure variation at monitoring points in a 3000 m tunnel with full methane condition: (a) time–history curve of pressure; (b) the peak pressure.

As shown in Figures 12b, 13b and 14b, an increase in tunnel length elevated the explosion pressure. When the tunnel length was 1000 m, the maximum explosion pressure was 55.74 kPa. As the length of the tunnel increased to 2 km, the maximum explosion pressure rose to 65.85 kPa. When the tunnel length reached 3 km, the maximum explosion pressure reached 94.82 kPa. The increase in tunnel length exerted a dual effect on methane: it raised internal ventilation pressure while simultaneously heightening the risk of methane accumulation, thereby amplifying the hazard of methane explosions.

As shown in Figure 15, by fitting the peak overpressure values from multiple monitoring points across methane tunnels of varying lengths, a relationship curve was derived between the peak overpressure of methane explosions and distance. The results demonstrated that the peak pressure at monitoring points decreased progressively with greater distance from the detonation point. The relationship between peak pressure and distance was not linear but conformed to a power function decay model, exhibiting a high degree of fit. This pattern underscored the complexity of explosion wave propagation within tunnels.



**Figure 15.** Fitted curves of peak overpressure of explosion shock waves as a function of distance in tunnels of varying lengths: (a) 500 m, (b) 1000 m, (c) 2000 m, and (d) 3000 m.

## 4. Discussion

Under different confinement conditions, methane enrichment behavior exhibits significant variations. In Model 1, although a natural diffusion pathway exists, the methane concentration still exceeds the lower explosion limit within a relatively short period. This indicates that relying solely on an upper opening is insufficient to effectively discharge accumulated gas, which may be attributed to poor airflow organization in the roadway or a high methane emission intensity. In Model 3, methane cannot escape, leading to a rapid rise and sustained maintenance of high concentration levels in a short time, representing the highest explosion risk. Model 2 demonstrates the best performance among the three scenarios. In this configuration, methane concentration in areas farther from the coal wall eventually decreases to below the lower explosion limit, indicating that the limited ventilation path formed by the connection between the bottom opening and the main roadway plays a positive role in diluting methane.

Regarding the propagation of methane explosion pressure, this study focuses on the influence of methane concentration distribution and roadway length on explosion pressure. Simulation results indicate that under fully premixed conditions, the peak explosion pressure is relatively low with minor variations among monitoring points. This suggests that the combustion reaction of a uniform methane-air mixture in a confined space is limited by oxygen supply, resulting in a more gradual energy release. In contrast, under partially premixed conditions, a higher peak explosion pressure and more frequent fluctuations are observed, reflecting the more complex turbulence and pressure feedback mechanisms involved in the combustion of non-uniform gas mixtures. This finding is consistent with previous studies on the enhanced effects of non-uniform flammable gas explosions.

Furthermore, tunnel length had a significant impact on the explosion pressure. As the tunnel length increased from 1 km to 3 km, the maximum explosion pressure rose from 55.74 kPa to 94.82 kPa. This phenomenon can be attributed to two aspects: firstly, multiple reflections and superposition of shock waves in longer tunnels lead to enhanced pressure accumulation; secondly, increased tunnel length raises the possibility of methane accumulation, thereby increasing the explosion severity. This finding provides important guidance for the ventilation design and explosion prevention in long blind headings.

## 5. Conclusions

This study systematically investigates the characteristics of methane diffusion, accumulation, and explosion in railway auxiliary tunnel through numerical simulation, elucidating the patterns of methane diffusion and accumulation under various sealing conditions, and analyzing the effects of methane concentration and tunnel length on the propagation and attenuation of explosion pressure. The specific findings are as follows:

- (1) Following methane emission from the coal seam, its migration within the railway auxiliary tunnel exhibits a distinct pattern: methane initially accumulates in the uphill section and subsequently diffuses downward under the influence of the concentration gradient, resulting in a higher methane concentration in the uphill section compared to the downhill section. Within a short timeframe, the methane concentration in the coal seam reaches a peak and remains stable.
- (2) During the methane accumulation process, the sealing configuration of the crosscut end faces significantly influences the methane concentration distribution. When the upper end face is sealed and the lower end face remains open, a localized safety zone emerges near the lower end face after 28 days, with the overall methane concentration being lower than that observed under the other two sealing configurations. Consequently, in practical engineering applications, it is recommended to maintain an

open lower end face, seal the upper end face, and prioritize monitoring of methane concentration in the uphill section.

- (3) Tunnel length and methane concentration are critical factors affecting the propagation of methane explosions. In the fully premixed methane case, the combustion reaction was limited by insufficient oxygen supply, reducing energy release and resulting in lower peak pressure. In contrast, under partial methane conditions, the explosion pressure propagated and released more easily within the tunnel, leading to higher peak pressure. When the length of the tunnel is relatively long, the explosion pressure rapidly peaks within a short period before dropping swiftly to negative pressure.
- (4) The fitted relationship between explosion overpressure and distance reveals a nonlinear correlation within a certain range: the farther the distance from the detonation point, the lower the overpressure, with the attenuation trend conforming to a power function model. The simulation results align closely with theoretical analyses, confirming the reliability of the findings.

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