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RESEARCH

Numerical analysis of the effect of ventilation door on the propagation characteristics of gas explosion shock waves

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Abstract Ventilation door are commonly found in tunnels and other underground engineering ventilation structures, disaster periods using its explosion isolation, explosion relief, wind regulation characteristics for disaster prevention and mitigation is of great significance. This paper numerically simulates the propagation characteristics of the gas explosion shock wave in the nearby tunnel when the ventilation door are opened at different degrees, and analyzes the influence mechanism of the opening degree on the change law of the shock wave overpressure distribution in the nearby tunnel. The results show that the shock wave forms a strong turbulence area (high pressure area) on both sides in front of the ventilation door, and the area range and the overpressure value decrease with the increase of the opening degree; the ventilation door reduce the intensity of the shock wave, so that the overpressure behind the ventilation door decreases, and the smaller the opening degree, the lower the overpressure behind the ventilation door. The secondary explosion formed shock wave and the ventilation door reflected shock wave meet to form a stronger shock wave, which leads to different opening degrees of ventilation door, its before, after the roadway and after the bifurcation of the main roadway in the measured points of the overpressure change curve is different, the main difference is that the peak overpressure for the first wave or the second wave peak. The peak overpressure in the tunnel before and after the ventilation door decreases and increases respectively with the increase of the opening length, and the overall decay of the peak overpressure at 5 m and 10 m before the ventilation door is 49.56% and 4.04% respectively and only has an effect on the peak overpressure in main tunnel within 20 m from the bifurcation.

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Article Highlights

- The influence of ventilation door opening degree on the propagation characteristics of gas explosion shock wave in nearby tunnels is studied.

With the increase of the opening degree, the area and overpressure value in front of the ventilation door decrease, and the ventilation door effectively reduces the strength of the shock wave. The interaction between the shock wave formed by the secondary explosion and the reflected shock wave of the ventilation door causes the overpressure change curve at different measurement points to change. The peak overpressure in the tunnel before and after the ventilation door decreases and increases with the increase of the length of the opening, respectively.

Keywords Ventilation door · Gas explosion · Numerical simulation · Opening degree · Overpressure peak

1 Introduction

Combustible gas explosion seriously threatens urban safety, normal operation of tunnels and safe mining of mines. Combustible gas explosion in production enterprises will not only stop production, but also seriously damage equipment and cause death (Ye et al. 2023; He et al. 2019)..Gas explosion shock wave in the closed space continuously propagated, reflected, resulting in the wall structure to withstand the peak overpressure increase, causing more serious damage and kill the consequences; gas explosion in the process of high-temperature flames will also cause personnel and equipment to be injured, and even trigger a secondary explosion, with great danger (Ye et al. 2023; Addai et al. 2017; Atay and Bayraktaroglu 2020; Meng et al. 2019).A large number of scholars have conducted research on the propagation characteristics of gas explosions and have achieved fruitful results. Li et al. (2020) studied the propagation characteristics of gas explosions of different volumes in a large experimental tunnel, and the results showed that, the larger the volume of gas involved in the explosion, the more intense the explosion and the farther the flame propagation. Ajrash et al. (2017) conducted an experimental study of the effect of pipe length on the explosion propagation of methane/air premixed gases using long straight pipes and showed that the explosion overpressure increased with the increase in pipe length. Sun et al. (Liu et al. 2023a) carried out a numerical simulation study on the propagation characteristics of gas explosion in pipes with four sections. The results show that the pipe section has a significant impact on the overpressure, temperature and flame burning rate of gas explosion. The bending and bifurcation structure of the pipeline also causes a strong mutual excitation between the gas explosion flame and the shock wave when the two pass through the structure (Zhang et al. 2023; Edwards et al. 2006; Liu et al. 2023b; Liu and Li 2023).Any object that blocks the propagation of the explosion shock wave is an obstacle, and the obstacle can block the propagation of the shock wave, promote the acceleration of the flame, and make the explosion overpressure near the obstacle aggravate and rise. Wang et al. (2018) set up three different shapes of obstacles (rectangular, square, spherical) in the square pipe(6.5 m×0.2 m×0.2 m) to study the effect of obstacles on the gas explosion flame and overpressure, and the results found that the flame will change the load through the obstacles of different shapes, and the rectangular obstacles have the greatest influence on the flow field, resulting in the highest overpressure value. Na'inna et al. (2017) carried out the effect of obstruction rate of obstacles and distance between obstacles on gas explosion propagation and showed that the maximum overpressure increases with the increase in the length of obstacles.

Excessive overpressure will bring serious damage, in order to reduce the damage of the explosion, a large number of scholars have also carried out research on explosion venting. Yu et al. (2018) studied the effect of different locations of pressure relief ports in a square straight pipe on the shock wave and flame propagation of a gas explosion. Guo et al. (2016) and Chen et al. (2020) carried out the effect of the number and location of pressure relief ports on the explosion overpressure using an experimental setup with pressure relief ports, and the results showed that the number and location of pressure relief ports had a limited effect on the explosion pressure. Sun et al. (2020) studied the effect of indoor upper gas temperature and flame height on the exterior wall surface when the windows were opened at different angles during an indoor fire, and the results showed that when the window opening angle was less than 60°, the indoor upper gas temperature increased and the flame height on the exterior wall surface decreased as the window opening angle increased. Zhao et al. (2022) studied the effect of pressure relief conditions on flame and overpressure through a set of experimental devices established to simulate the natural gas explosion process in comprehensive pipe gallery, and the results showed that different pressure relief locations and pressure relief intensities have a great influence on the explosion characteristics of comprehensive pipe gallery. Wang et al. (2020) studied the damaging factors of gas explosion shock wave on mine ventilation system and the attenuation law of explosion wave in roadway space, and designed a ventilation door with automatic pressure relief and reset under overpressure to reduce the destructive effect of explosion shock wave. Sun et al. (2021) conducted a study on the effectiveness of ventilation blast doors in isolating gas explosion shock waves and the results showed that after using ventilation blast doors, the maximum gas explosion overpressure was significantly reduced by 21% and the shock waves at the rear of the explosion pipeline were significantly suppressed.

Ventilation door commonly exist in tunnels and other underground projects, under normal circumstances used to regulate the amount of wind. When a gas explosion occurs in the tunnel, the ventilation door undoubtedly become an obstacle in the propagation of the blast shock wave, due to the ventilation door can be opened under the force of the characteristics of the blast shock wave propagation has a certain inhibitory effect. In this paper, we analyze the influence mechanism of adjusting ventilation door on the propagation characteristics of explosion shock waves by simulating the propagation process of gas explosion shock waves at different opening degrees of ventilation door in underground excavation workings. The results of the study can provide guidance for the use of ventilation door-type structures to weaken the destructive effects of blast shock waves.

2 Material and methods

2.1 Physical model

The common ventilation system of the heading face in the mine production system is shown in Fig. 1a. The fresh air flow from the air intake rise roadway is pressed into the head of the excavation face by local ventilators and air ducts, and the dirty air is discharged along the roadway, and the total inlet air volume of the excavation face is determined by the air supply capacity of the local fan and the degree of opening of the ventilation door. For the convenience of research, it is simplified into a 3D model of the excavation face as shown in Fig. 1b, with a length of 140 m, a width of 3 m and a height of 3 m, and a return air connection roadway of 40 m long, 3 m wide and 3 m high. Near the left end of the model is the gas accumulation area, the fire source is located in the center 0.5 m from the left end, and the fire source is shaped as a sphere with a radius of 0.5 m. In order to study the influence of damper opening degree on the propagation of shock wave overpressure, 7 monitoring points were set up before and after the ventilation door and in the tunnel, as shown in Fig. 1b.

2.2 Grid setup

In numerical simulation, the grid size is directly related to the correctness and rationality of the simulation results. When the grid is larger, the simulation results are rougher and may not reflect some important data and parameter variation characteristics; as the grid decreases, the simulation data will become closer to the experimental values; but when the grid size is set smaller, the computer requirements are higher and the simulation time is longer. After comprehensive analysis, the grid size is chosen as 0.2 m and the number of grids is 201,625.

2.3 Mathematical model

Mine gas explosion is essentially combustible gas in a limited space is ignited, followed by the development of explosive boom, mine gas explosion is essentially combustible gas in a limited space is ignited, followed by the development of explosive boom, when the combustible gas reflects the completion can be equated to high pressure gas propagation in the tunnel, the entire reaction process can be described by the following equation.

Continuity equation:

$$\frac{\partial p}{\partial t} + \frac{\partial (pu)}{\partial x} + \frac{\partial (pv)}{\partial y} + \frac{\partial (pw)}{\partial z} = 0 \tag{1}$$

Energy equation:

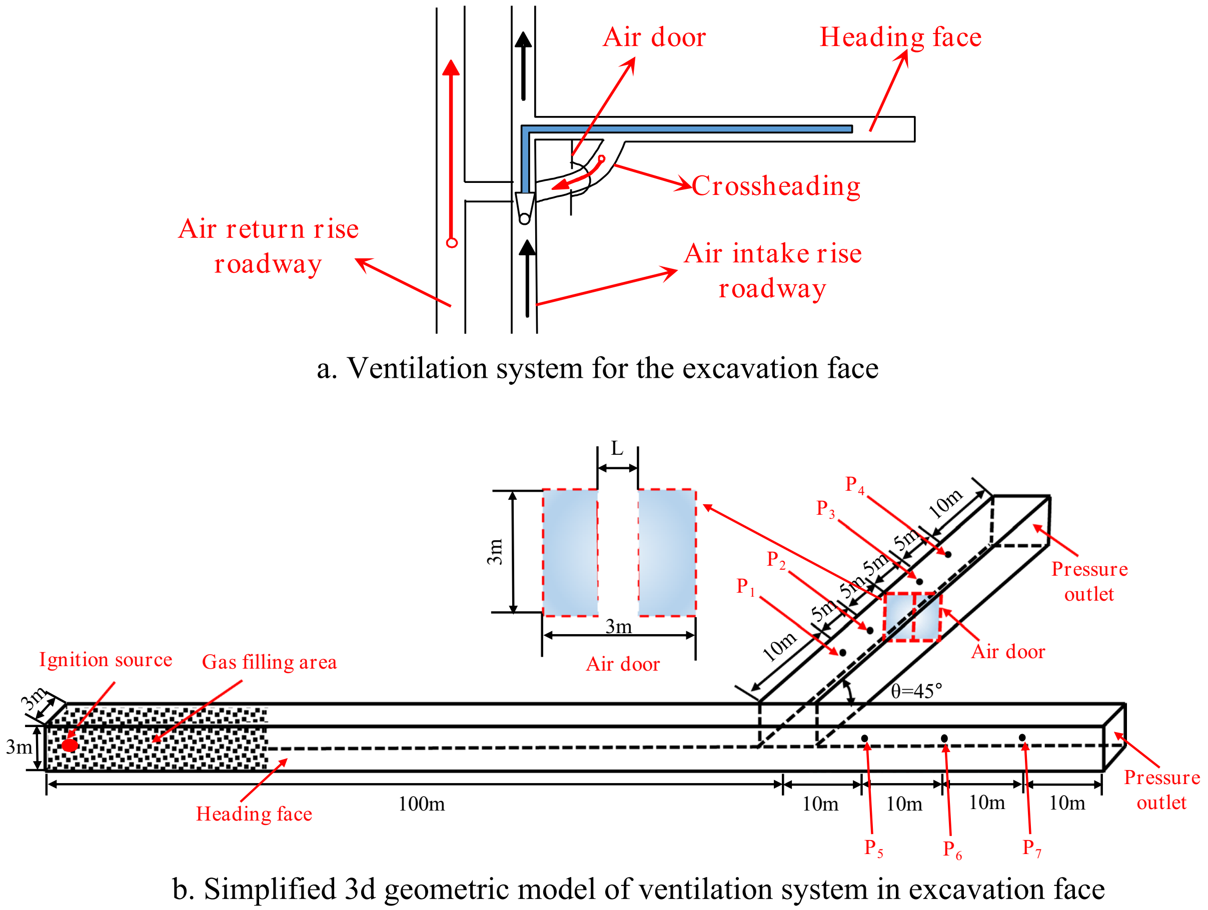


Fig. 1 Ventilation system and 3d geometric model of excavation face. **a** Ventilation system for the excavation face. **b** Simplified 3d geometric model of ventilation system in excavation face

$$\frac{\partial e}{\partial t}+u\frac{\partial e}{\partial x}+v\frac{\partial e}{\partial y}+w\frac{\partial e}{\partial z}=0 \tag{2}$$

Momentum equation:

$$\frac{\partial \rho u}{\partial t}+\frac{\partial(\rho uu)}{\partial x}=-\frac{\partial p}{\partial x}+\frac{4}{3}\mu_e\frac{\partial u}{\partial x} \tag{3}$$

State equation:

$$p=p(\rho,T)=\rho RT \tag{4}$$

where P is pressure, Pa; t is time, s; x, y, z represent rectangular coordinates, respectively; u, v, w represent the velocity in the corresponding direction, respectively; ρ is fluid density, kg/m^3; T is

temperature, K; R is gas constant; e is specific energy, $e=p/(\gamma\text{-}1)+\rho(u^2+v^2+w^2)/2,\gamma$ denotes gas index.

Combustion model and turbulent flame velocity model:

$$R_{fu}=-\min(\left|R_{i,fu}\right|,\left|R_{j,fu}\right|) \tag{5}$$

$$R_{i,fu}=v'_{i,fu}M_{\omega,i}A\rho\tau_{sgs}^{-1}\min(\frac{Y_{i,fu}}{v_{i,fu}M_{\omega,fu}}) \tag{6}$$

$$R_{j,fu}=v'_{j,fu}M_{\omega,j}AB\rho\tau_{sgs}^{-1}\frac{\sum_j Y_{j,fu}}{\sum_j^N v''_{j,fu}M_{\omega,j}} \tag{7}$$

$$\tau_{sgs}^{-1}=\sqrt{2S_{ij}S_{ij}} \tag{8}$$

where $Y_{i,fu}$ is the mass fraction of any production species; Yj,fuis the mass fraction of a particular reactant; A,B is empirical constant equal to 4.0 and 0.5 respectively; $\tau^{-1}{}_{sgs}$ is subgrid-scale mixing rate; S_{ij} is strain rate tensor.

The gas explosion is a non-stationary process with no slip on the model walls. The iterative solution is performed using Simple algorithm with an iteration step of 0.0005 s. This mathematical model has been demonstrated in the literature to simulate the gas explosion shock wave propagation process (Zhang et al. 2021, 2020; Zhang et al. 2022). Zhang et al. (2021) also used this mathematical model to verify the experimental results of the blast propagation experiments carried out in the experimental system shown in Fig. 2 by numerical simulation, which also verified the reliability of this model.

2.4 Working condition setting

In order to study the influence of the opening degree of ventilation door on the propagation of gas explosion shock waves, as shown in Fig. 1b, five kinds of ventilation door opening length L, i.e., 0.5 m, 1.0 m, 1.5 m, 2.0 m, 2.5 m are respectively set and corresponding to the explosion venting area A of 1.5 m^2, 3 m^2, 4.5 m^2, 6.0 m^2, 7.5 m^2, respectively. The propagation process of gas explosion shock wave in the excavation face under the working condition of five ventilation door opening lengths is simulated.

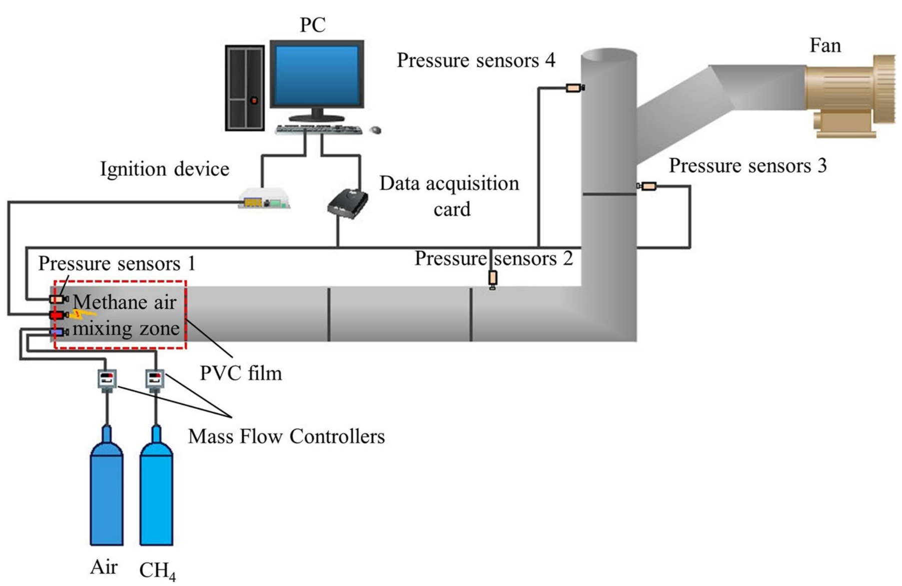
3 Results and discussion

3.1 Gas explosion shock wave propagation characteristics of the excavation face

Figure 3 shows the propagation process of gas explosion shock wave in the roadway of the excavation face with the opening length of ventilation door L = 1.5 m (explosion venting area A = 4.5 m^2).

It can be seen from Fig. 3 (1) After the gas in the gas accumulation area is detonated, the pressure wave expands outward in the form of spherical wave at the initial stage of explosion, and over time under the influence of the restriction and reflection of the roadway wall, the generated shock wave gradually evolves into a plane pressure wave and propagates forward in this form; (2) Before the plane pressure wave propagates to the roadway bifurcation, a secondary explosion occurs as the unburned gas is ignited, and a second high pressure zone appears. At this time, the intensity of the shock wave generated by the secondary explosion is less than that of the first explosion; (3) The shock wave generated by the first explosion passes through the roadway bifurcation, part of which continues to propagate along the straight roadway, and part of which propagates along the bifurcation to the roadway where the ventilation door is located; The shock wave propagating in the direction of the ventilation door is retroactively reflected after being blocked by the ventilation door. The reflected shock

Fig. 2 Small size gas explosion propagation experiment system diagram



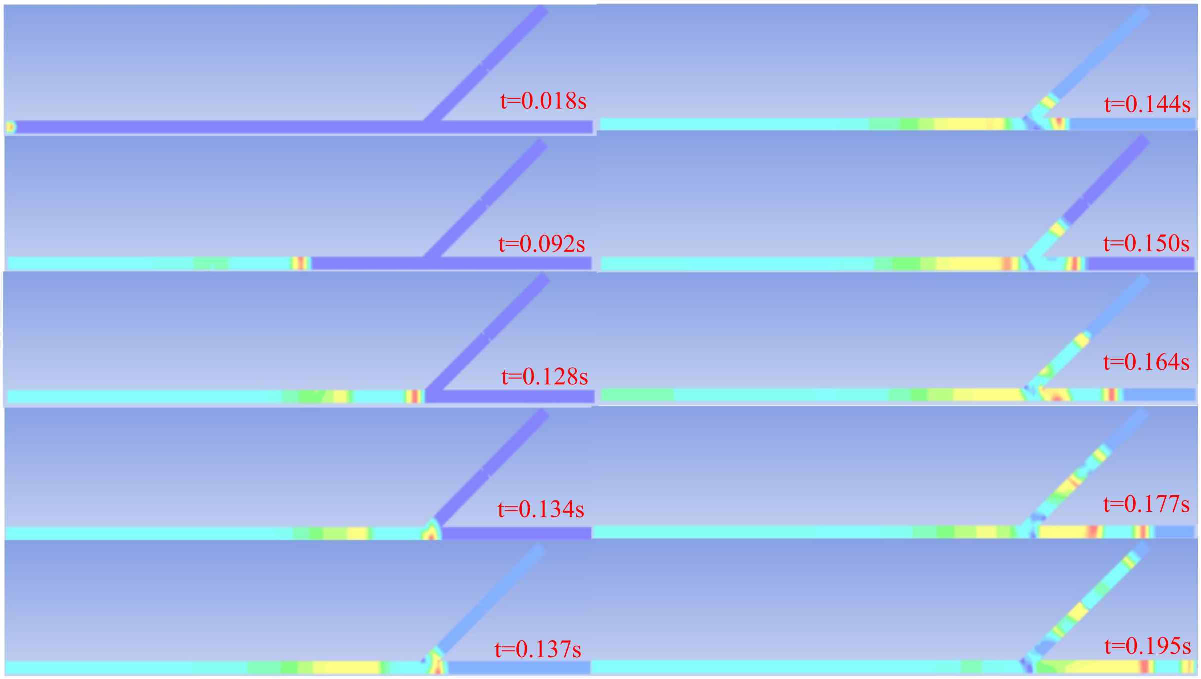


Fig. 3 The process of gas explosion shock wave propagation at the head of the excavation face (A = 4.5 m^2)

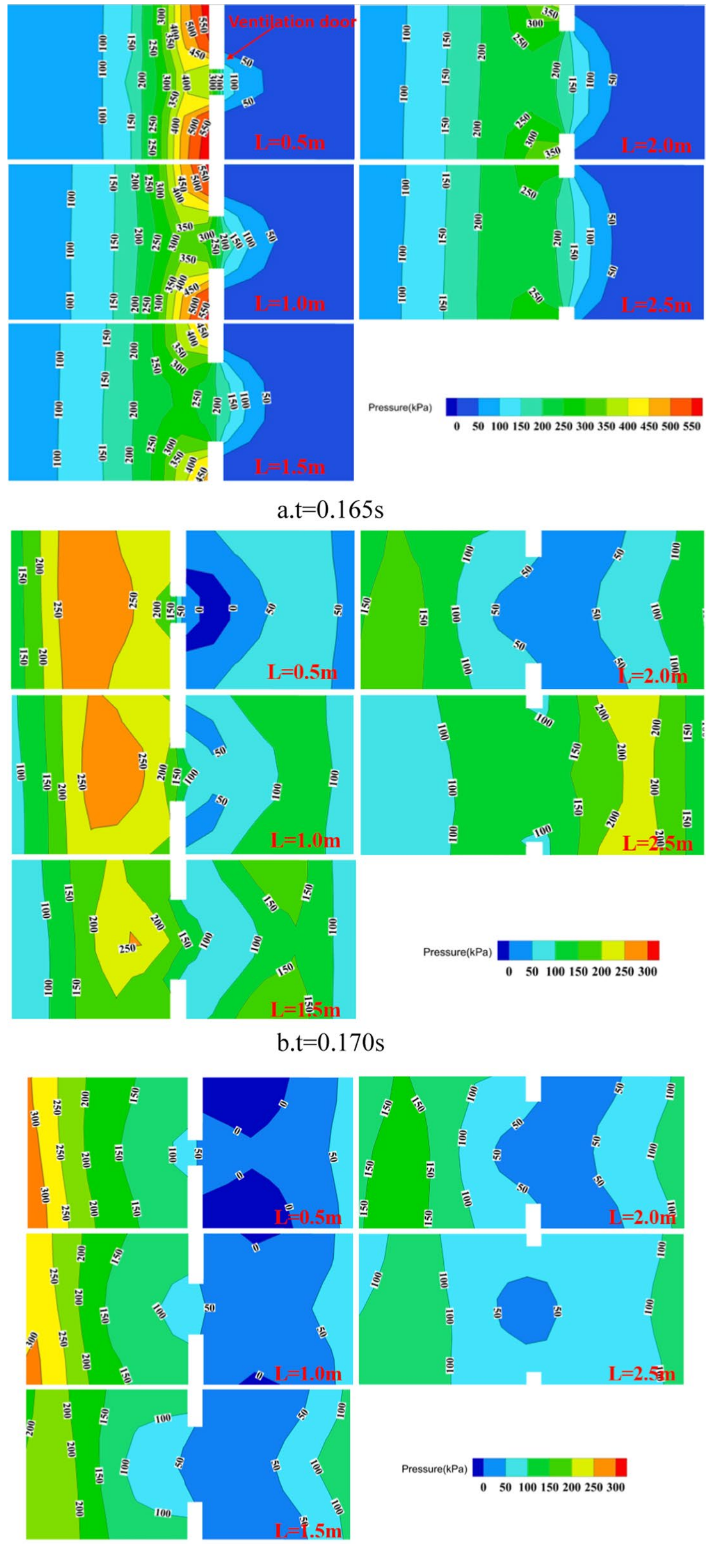
wave generated meets the shock wave generated by the secondary explosion to form a mixed shock wave, which increases the strength and propagation speed of the secondary explosion shock wave. The distance between the front edge of the explosion shock wave generated by the first explosion and the front edge of the mixed shock wave gradually decreases; Finally, the strength of the mixed shock wave exceeds that of the first explosion.

3.2 The effect of the degree of opening the ventilation door on the distribution of shock wave overpressure

After the gas explosion occurred at the head of the excavation face, the shock wave overpressure distribution in the connection roadway near the ventilation door when the ventilation door are opened to different degrees is shown in Fig. 4.

As can be seen from Fig. 4(1) shock wave reaches the ventilation door near (t = 0.165 s), the shock wave in the ventilation door on both sides of a strong reflection effect, resulting in both sides of the overpressure high-pressure area;The greater the opening degree of the ventilation door, the better the explosion relief effect, the smaller the range of high pressure zone on both sides of the ventilation door, and the smaller the overpressure value. The opening length L of the ventilation door increases from 0. 5 to 2.5 m, and the overpressure decreases from 550 to 250 kPa.The overpressure at the ventilation door decreases with the increase of the opening degree of the ventilation door. The opening length L of the ventilation door r increases from 0.5 to 2.5 m, and the overpressure at the ventilation door decreases from 350 to 150 kPa. In general, at this time, the distribution law of shock wave overpressure in the connection roadway near the ventilation door is basically consistent with different opening degrees of the ventilation door.2) With the extension of time (t = 0.170 s), the shock wave continuously passes through the ventilation door, and the distribution law of the shock wave overpressure in the area near the ventilation door becomes different when different ventilation door are opened. With the increase of the opening degree of the ventilation door, the shape of the shock wave front in the area behind the ventilation door evolved from the hemispherical shape to V-shaped, and then to nearly plane waves, and there were two vortex areas behind the ventilation door when the ventilation door were opened at

Fig. 4 Shock wave overpressure contour diagram at different opening lengths of dampers (connection roadway)



a.t=0.165s

b.t=0.170s

c.t=0.175s

1.0 m. With the increase of the ventilation door opening degree, the shape of the shock wave front in the area near the front of the ventilation door evolves from hemispherical to vortex, then to small vortex, then to V-shaped, and finally to near plane wave. (3) With the further extension of time (t = 0.175 s), the shock wave continuously into the ventilation door, the ventilation door in front of the pressure relief area is getting bigger and bigger, the ventilation door open different degrees when the ventilation door behind the shock wave front surface basically tends to be the same, the difference is that the ventilation door open 2.5 m when the dampers open by the impact of the reflection of the shock wave on both sides to form a vortex.

The distribution of shock wave overpressure in the excavation roadway behind the bifurcation at different opening degrees of the ventilation door is shown in Fig. 5.

As can be seen from Fig. 5(1) the overall impact of the degree of opening of the ventilation door on the shock wave overpressure distribution in the excavation roadway behind the bifurcation is small, and only has an impact on the overpressure distribution in the 15 m range of the tunnel near the bifurcation; and with the extension of the shock wave propagation time, the impact of the degree of opening of the ventilation door on the shock wave overpressure distribution in the excavation roadway behind the bifurcation gradually decreases, When the propagation time of the shock wave is 0.2 s, the overpressure distribution of the shock wave in the tunnel behind the bifurcation is basically the same with different opening degrees of the ventilation door. 2) With the superposition of the second blast shock wave and the reflected shock wave from the ventilation door, the intensity of the mix shock wave gradually exceeds the intensity of the first blast shock wave.

3.3 The influence of the degree of ventilation door opening on the change curve of shock wave overpressure

After the gas explosion occurred at the head of the excavation face, the distribution of the shock wave overpressure change curve at the monitoring points P1 and P2 in front of the ventilation door when the ventilation door are opened at different degrees is shown in Figs. 6 and 7.

As can be seen from Fig. 6, monitoring point P1 is far away from the ventilation door (10 m before the ventilation door), the ventilation door open different lengths, the first wave peak is the location of the maximum overpressure value, the peak moment is also basically the same. However, the degree of opening the ventilation door on the overpressure variation curve has a certain impact, especially when the ventilation door open the length of 0.5 m, affected by the strong reflection of shock waves on both sides of the ventilation door, the reflected shock waves and subsequent shock wave encounter superimposed and formed in 0.193 s, 0.212 s, respectively, the third and fourth wave peak. With the ventilation door open degree of increase, the shock wave reflection effect is getting weaker and weaker, When the opening length of the ventilation door is 2.0 m, the overpressure change curve is basically the same as the change curve without the influence of obstacles.

It can be seen from Fig. 7 that: (1) the propagation of the shock wave to the ventilation door is blocked, forming a strong turbulence near the ventilation door, forming a positive feedback mechanism with the high-temperature air mass, which increases the overpressure near the ventilation door; (2) Monitoring point P2 is closer to the ventilation door 5 m in front of the ventilation door), and is more affected by the reflection of shock waves; as the opening area of the ventilation door increases, the overpressure curve shape changes, and the ventilation door open length is less than or equal to 1.5 m, the second wave peak is maximum overpressure value at this location, and its maximum overpressure value is much higher than the peak of P1 point; after the opening length is greater than 1.5 m, the impact reflection formed near the ventilation door is weak, no strong turbulence is formed, and the increase in overpressure near the ventilation door is limited, the first wave peak is maximum overpressure value at this location, The maximum overpressure is lower than the P1 peak value. (3) The time of maximum overpressure value first increases and then decreases with the increase of the opening degree of the ventilation door (0.179 s → 0.183 s → 0.157 s). When the opening length is 1.5 m, the time of maximum overpressure value is the latest (0.183 s).

After the gas explosion occurred at the head of the excavation face,The distribution of shock wave overpressure change curves at monitoring points P3

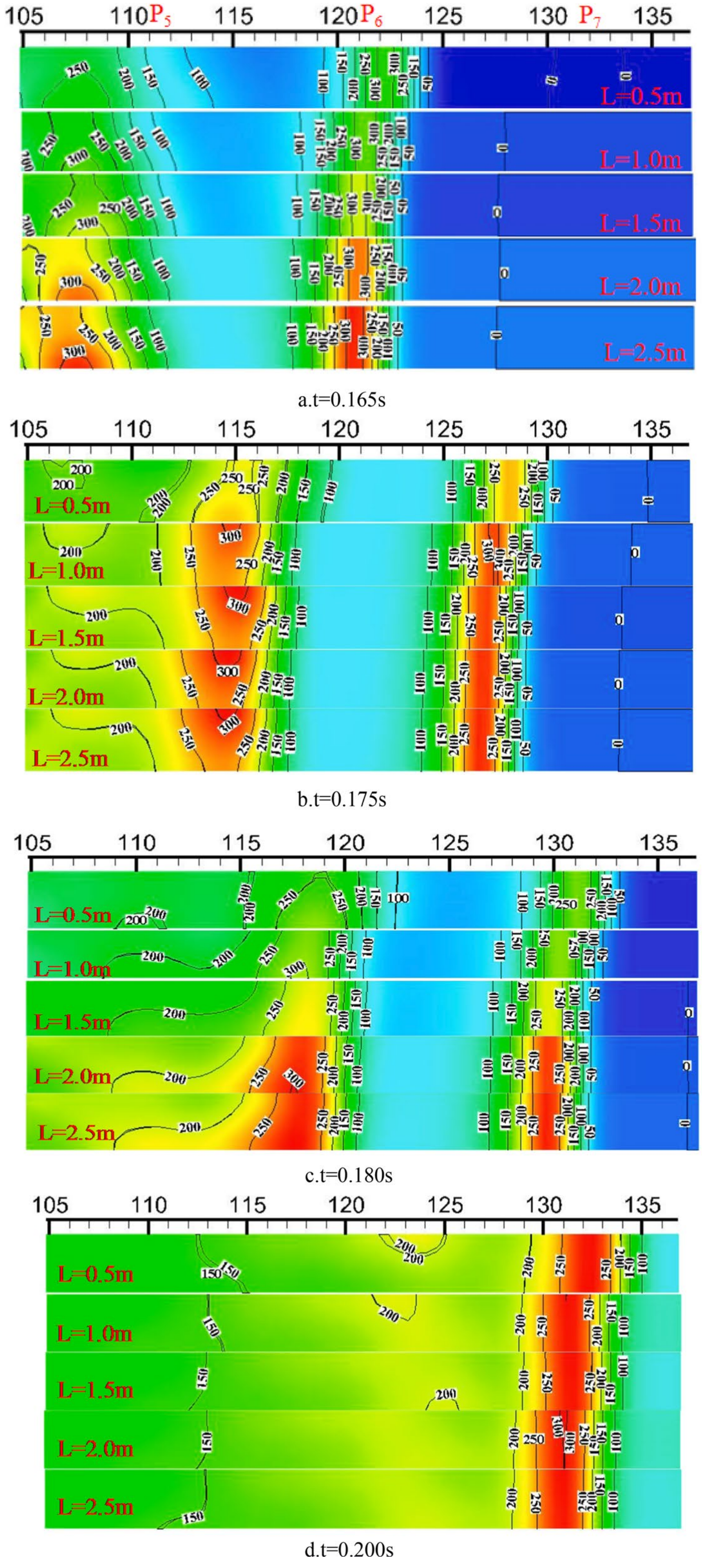


Fig. 5 Shockwave overpressure contour map for different opening lengths of ventilation door (excavation roadway behind the bifurcation)

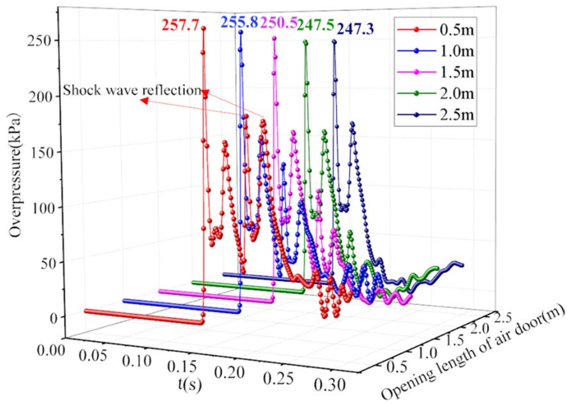


Fig. 6 Variation curve of overpressure at point P1

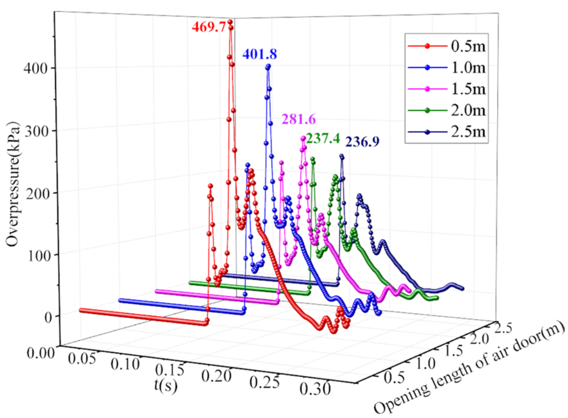


Fig. 7 Variation curve of overpressure at point P2

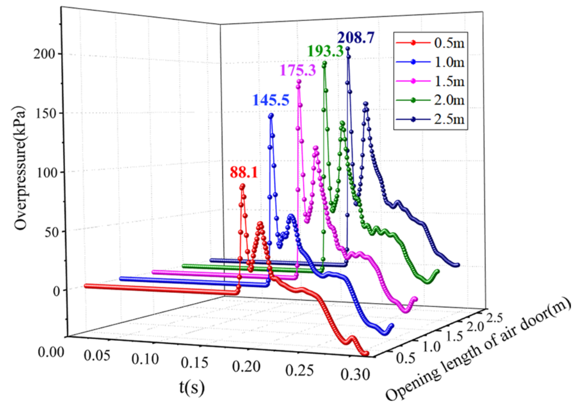


Fig. 8 Variation curve of overpressure at point P3

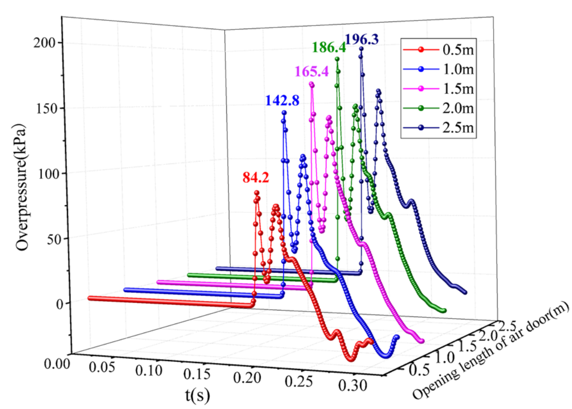


Fig. 9 Variation curve of overpressure at point P4

and P4 after the ventilation door at different opening degrees are shown in Figs. 8 and 9.

As can be seen from Figs. 8 and 9(1) Although the shock wave propagates to the ventilation door to form strong turbulence and form a positive feedback mechanism with the high-temperature air mass, the obstructive effect of the ventilation door dominates this process, and the strong impact collision makes a large loss of shock wave energy, and the ventilation door reduce the intensity of the shock wave, so that the overpressure after the ventilation door decreases. The smaller the degree of opening the ventilation door, the more obvious the obstruction of the ventilation door, the more violent the impact collision between the shock wave and the ventilation door, the more shock wave energy loss, the lower the overpressure of the shock wave behind the ventilation door. Different opening degree of the ventilation door on P3, P4 point shock wave overpressure curve shape has no effect, P3, P4 point shock wave is the existence of two peaks, the first wave peak is the maximum overpressure value. But the different opening degree of the ventilation door has a great impact on the maximum overpressure of the P3, P4.the greater the opening degree of the ventilation door, the better the ventilation door pressure relief effect, the higher the maximum overpressure after the ventilation door, and the farther away from the ventilation door the lower the maximum overpressure. With the increase in the degree of opening the ventilation door, the maximum overpressure moment slightly shortened,the opening length of the ventilation door increases from 0.5 to 2.5 m, and the peak time of P3 and P4 points decreases from 0.178 and 0.189 to 0.176 s and 0.186 s respectively.

The change curves of shock wave overpressure at P5, P6 and P7 points in the excavation roadway behind the bifurcate at different opening degrees of the ventilation door are shown in Figs. 10, 11 and 12.

From Figs. 10, 11 and 12, we can see that: (1) The degree of opening of the ventilation door has no effect on the shape of the shock wave overpressure curve in the excavation roadway near the back of the bifurcation, and the overpressure change curves at points P5 and P6 (10 m and 20 m from the bifurcation respectively) are still in the shape of typical two-wave peaks, with the first wave being the maximum overpressure at this measurement point. (2) The overpressure change curve at point P7 (30 m from the bifurcation) is still a two-wave peak curve, but the second wave peak becomes the maximum overpressure at this measurement point due to the superposition of the secondary explosion shock wave and the reflected shock wave from the ventilation door. (3) With the increasing degree of opening the ventilation door, the difference between the first and second wave peaks at points P5 and P6 first decreases and then increases, and the difference between the second and first wave peaks at point P7 first increases and then decreases.

3.4 Impact of the degree of opening of the ventilation door on the peak shock wave overpressure

The variation curves of the maximum overpressure in the connection roadway near the ventilation door and

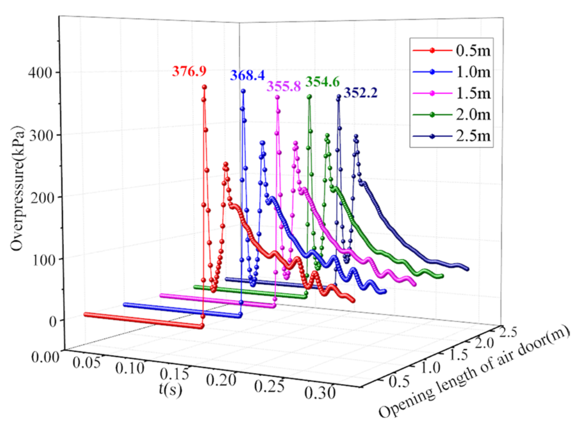


Fig. 10 Variation curve of overpressure at point P5

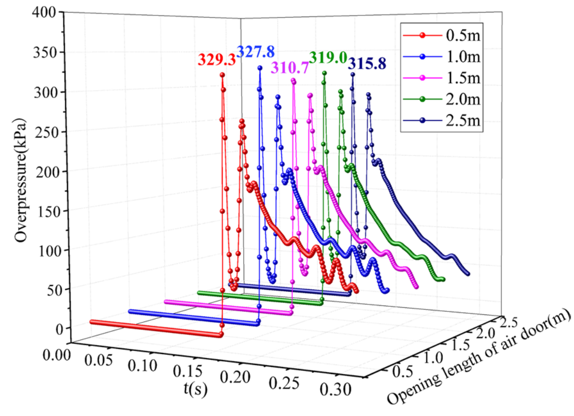


Fig. 11 Variation curve of overpressure at point P6

the maximum overpressure in the excavation roadway behind the bifurcation with different lengths of the ventilation door opening are shown in Figs. 13 and 14.

As can be seen from Fig. 13, The maximum overpressure at each point in front of the ventilation door decreases with the increase of the ventilation door opening length, and the overall attenuation amplitude of the maximum overpressure value at point P2 is greater than that at point P1.When the ventilation door opening length is changed from 0.5 to 2.5 m, the maximum overpressure at point P1 is attenuated from 257.7 to 247.3 kPa, which is attenuated by 4.04%, and the maximum overpressure at point P2 is attenuated from 469.7 to 236.9 kPa, which is attenuated by 49.56%.This is because the smaller the opening length of the ventilation door,

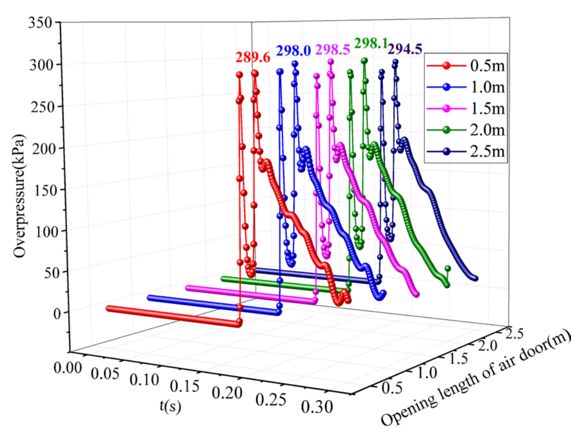


Fig. 12 Variation curve of overpressure at point P7

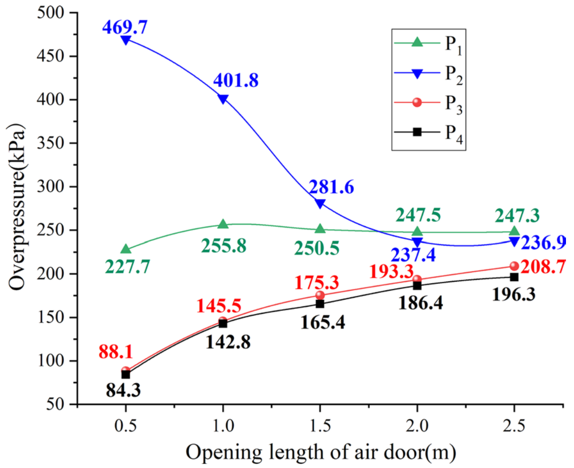


Fig. 13 Peak value change curve of overpressure in the connecting roadway near the ventilation door with different opening lengths

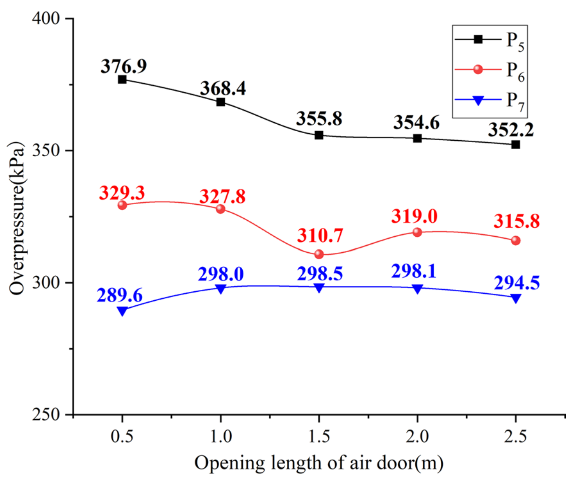


Fig. 14 Peak value change curve of overpressure in the excavation roadway behind the bifurcation with different opening lengths

the stronger the resistance of the ventilation door to the propagation of the shock wave, and the stronger the reflected shock wave formed. The stronger the turbulence intensity in the turbulent region formed at the position in front of the ventilation door, so that the maximum overpressure near the position in front of the ventilation door decreases with the increase of the opening length. At the same time, the closer to the ventilation door, the more pronounced the influence of the reflected wave. Therefore,the maximum overpressure at point P1 is less affected by the degree of opening than point P2.

For the maximum overpressure at each point in the tunnel behind the ventilation door increases with the opening of the ventilation door and decreases with the increase of the distance between the ventilation door. This is because the longer the length of the ventilation door open, the smaller the obstruction of the ventilation door on the propagation of shock waves, the less energy loss when the shock waves pass through the ventilation door, the greater the maximum overpressure at each position behind the ventilation door, the shock waves along the unobstructed roadway propagation follows the law of attenuation along the roadway, so the farther away from the ventilation door after ventilation doors, the smaller the maximum overpressure.

It can be seen from Fig. 14 that In the tunnel roadway behind the bifurcation, the closer to the bifurcation,the greater the maximum overpressure is affected by the length of the ventilation door opening. The maximum overpressure of point P5 in the tunneling roadway 10 m away from the bifurcation gradually decreases with the increase of the opening length of the ventilation door and the amplitude of the decrease is smaller and smaller, because the P5 point is affected by the shock wave transmitted from the tunneling roadway and the reflected shock wave propagated from the contact lane where the ventilation door is located, and the smaller the degree of opening of the ventilation door, the stronger the reflected shock wave strength generated, so that the maximum overpressure at point P5 is also greater. The greater the degree of opening of the ventilation door, the smaller the obstruction effect on the explosion shock wave, so that the intensity of the reflected shock wave propagated to P5 from the contact lane is smaller, so that the maximum overpressure at P5 point is smaller and the amplitude is reduced. The P6 point in the tunneling roadway 20 m away from the bifurcation is affected by the double influence of the ventilation door opening degree and the right exit boundary, and its maximum overpressure fluctuates around 5% with the increase of the ventilation door opening length, and the overpressure peak is the largest when the ventilation door opening length is 0.5 m.

The shock wave reflected from the contact lane where the ventilation door is located loses a lot of energy through the section burst of the bifurcation and the change of propagation direction, and the area that can be affected is limited, the maximum overpressure of P7 point in the tunneling roadway 30 m away from the bifurcation increases first and then decreases with the increase of the ventilation door opening length, the overall change fluctuates little at about 3%, and the peak overpressure is the largest when the ventilation door opening length is 1.5 m. In general, the area of the tunnel roadway 20 m behind the bifurcation is already very little affected by the degree of ventilation door opening.

4 Conclusion

(1) After the gas accumulated in the excavation work area was ignited and exploded, the shape of the explosion pressure wave underwent a transformation from spherical wave to plane wave, Before it propagated to the bifurcation, the incompletely burned gas was burned again to form a secondary explosion, forming a second high-pressure area in the roadway. After the shock wave is obstructed by the ventilation door, it is reflected, and the reflected shock wave generated meets the shock wave generated by the secondary explosion to form a mixed shock wave of greater intensity, which continues to propagate to the tunneling roadway behind the bifurcation.

(2) After the shock wave reaches the dampers, a strong reflection occurs on both sides in front of the ventilation door to form a strong turbulence area, forming a high pressure area on both sides of the ventilation door, the greater the ventilation door open, the smaller the range of high pressure areas on both sides of the ventilation door, the smaller the overpressure value. The shape of the shock wavefront in the area near the back of the ventilation door evolves from a hemispherical shape to a V-shape and then to a near-plane wave. The overall impact of the ventilation door on the shock wave overpressure distribution in the tunneling roadway behind the bifurcation is small, and it only has an impact on the overpressure distribution within about 20 m of the tunnel near the bifurcation.

(3) Farther away from the front of the ventilation door at the location (10 m), the smaller the degree of opening of the ventilation door to produce the stronger the impact of the reflected wave intensity, the ventilation door opens the length of 0.5 m when its overpressure change curve for the 4 peaks, there are two peaks formed by the impact of reflected waves. When the opening length of the ventilation door is greater than 0.5 m, the shape of the overpressure curve is two peaks. When the opening length of the ventilation door is less than or equal to 1.5 m at the position (5 m) close to the ventilation door, the second peak is the maximum overpressure value, and after the opening length is greater than 1.5 m, the first peak is the maximum overpressure value. The degree of ventilation door opening has no effect on the shape of the overpressure curve of the measuring point in the roadway behind the ventilation door, and there are two peaks, the first of which is the maximum overpressure value. In the tunneling roadway behind the bifurcation, the overpressure change curve at the position closer to the bifurcation (P5 and P6) is still a typical two-wave peak shape, the first peak is the maximum overpressure value of the measurement point, and the overpressure change curve at the position farther from the bifurcation (P7) is still a two-wave peak curve, but the second peak is the maximum overpressure value of the measurement point.

(4) The peak overpressure in the tunnel before and after the ventilation door decreases and increases respectively with the increase of the opening length, The closer the ventilation door front is to the ventilation door, the greater the attenuation amplitude of the whole; In the tunneling roadway after the bifurcation, the closer to the fork, the greater the overpressure peak is affected by the opening length of the ventilation door, and the impact area is about 20 m after the bifurcation.

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Data availability Some or all data, models, or codes generated or used during the study are available from the corresponding author by request.

Declarations

Ethical approval and consent to participate Not applicable, Ethics approval was not required for this research.

Consent to publish All authors consent to the publication of this paper.

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