

Article

Experimental Study on the Effect of Sealing Time on Combustion State of the Fuel-Ventilation Controlled Wood Crib

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Abstract: A tunnel fire may gradually change from a fuel-controlled fire to a ventilation-controlled fire during the sealing process, so it is of great significance to study the influence of sealing time on the combustion state for safety control. In this study, an unsealed wood-crib fire test was first carried out using a reduced-scale tunnel model. When the wind velocity is 0.10 m/s, the wood crib is fuel-controlled. Based on this, the combustion state of a wood-crib fire was studied experimentally when the sealing time was 1 min, 3 min, 7 min, and 10 min. The results showed that after sealing, the flame orientation is approximately vertical, and as the sealing time increases, the carbonization of the wood crib becomes more pronounced. The ratio of X_{CO}/X_{CO_2} exceeds 0.057 1 min after sealing, and the wood-crib fire becomes ventilation-controlled. When the sealing time is 7 min and 10 min, the increase rate of X_{CO}/X_{CO_2} is faster than when the sealing time is 1 min and 3 min. The earlier the initial sealing time, the better the fire can be suppressed. During the sealing process, the temperature on the downwind side of the fire source decreases exponentially. This study aims to provide a reference for the application of sealing technology in tunnel fires.

Keywords: tunnel fire; sealing time; flame morphology; ventilation-controlled; fuel-controlled



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1. Introduction

With the rapid development of the global economy and the gradual increase in the urban population, tunnel construction and underground engineering remain indispensable and maintain a high-speed growth trend in the 21st century [1]. While the increasing number of tunnels has brought us more convenience and benefits, the number of related traffic safety accidents is also increasing year by year. Fire is one of the largest risks in the whole life cycle of a tunnel. Although fire has a low probability of occurring, the economic loss and social harm it causes are enormous [2]. For example, a fire occurred in the Kaprun tunnel in Austria in 2000, resulting in 8 deaths and 18 injuries, and in 2019, a fire occurred in the Maoliling tunnel of the Shenhai Expressway in Zhejiang Province, China, causing 5 deaths, 31 injuries, and economic losses totaling CNY five million [3].

Due to the narrow and relatively enclosed spatial structure of tunnels, once a fire occurs, the high-temperature smoke it generates is difficult to discharge, resulting in a sharp increase in toxic gas content. In addition, visibility is drastically reduced, posing great challenges to escape and fire rescue efforts [4]. Smoke is the main factor that endangers lives in a tunnel fire. Therefore, scholars at home and abroad have carried out extensive research on smoke diffusion laws [5,6] and smoke control strategies [7,8] in tunnel fire scenarios. Tunnel ventilation and smoke extraction systems, such as longitudinal ventilation systems [9], transverse ventilation systems [10], and semi-transverse ventilation systems [11], are widely used to control tunnel fire smoke. Various key issues of tunnel ventilation

systems, including critical wind velocity [12], maximum smoke temperature [13], longitudinal temperature distribution [14], and point smoke exhaust [15], have been studied by researchers using experimental and numerical simulation methods.

Although smoke from fires can be effectively controlled using ventilation, the flames continue to burn until the combustibles are exhausted, and this continuous combustion causes harm to the tunnel's structure and facilities. Related studies have shown that when a fire occurs in a tunnel, the fire can be directly extinguished by sealing the entrance and exit of the tunnel, reducing the burning time and thus minimizing losses [16]. Yao et al. [17] studied the maximum increase in gas temperature beneath the ceiling in a 1/15 reduced-scale tunnel. Their findings revealed that the maximum gas temperature increase had a 3/4 power relationship with the dimensionless fire source size. Chen et al. [18] conducted experiments in a 1/9 reduced-scale tunnel to investigate the effect of different sealing ratios on ceiling temperature. Their results showed that there existed a critical sealing ratio closely related to the fuel area at which the ceiling temperature inside the tunnel would reach a maximum. Ma et al. [19] used a combination of experimental and numerical analysis methods and found that when the sealing rate exceeds 50%, it could effectively isolate the oxygen supply and inhibit the development of a tunnel fire, and the GA-SVM prediction model was thus established to predict smoke temperature. Huang et al. [20] studied the variation in fire smoke temperature under different fire source power and sealing rates using numerical simulation. It was observed that the ceiling temperature increased with the sealing ratio when the heat release rate was relatively small, and when the heat release rate was relatively large, the longitudinal ceiling temperature decreased with the increase in the tunnel entrance sealing ratio at the initial stage and then tended to stabilize. Fernandez [21] used CFD numerical software to simulate the influence of sealing the area affected by the collapse in an actual mine on fire behavior and obtained a model able to define the behavior of a fire in the collapsed area of a descending sublevel coal mine.

The method of sealing tunnels to extinguish fires is based on the principles of isolating oxygen and inhibiting combustion oxygen consumption. When the amount of oxygen is insufficient or exhausted, the oxygen in the tunnel cannot be replenished, and the fire is suffocated until it is extinguished [22]. This means that the fire may gradually change from fuel-controlled to ventilation-controlled after sealing [23]. Fire under ventilation control is very dangerous due to incomplete combustion and many unburned and toxic components are present in the smoke [24]. However, current research mainly discusses the changes in parameters such as temperature and flue gas concentration in the tunnel fire under different sealing ratios and different sealing conditions at both ends of the tunnel. There is a lack of research on the importance of sealing timing in the conversion of combustible combustion types, and the combustibles used in related research are mostly oil substances. In fact, the combustible materials in tunnel fires are mainly solid. Research shows that a wood-crib fire can be roughly consistent with an actual tunnel fire with respect to temperature change during the combustion process [25]. Therefore, in this study, a wood-crib fire was selected as the fire source to study the influence of sealing time on the combustion state of combustibles to provide a reference for tunnel fire prevention and control.

2. Determination of Fire Burning Type

The mass flow ratio of CO to CO₂ is an important indicator used to reflect a ventilation-controlled fire and is expressed as $\dot{m}_{\text{CO}}/\dot{m}_{\text{CO}_2}$. When it begins to increase considerably, it is an indicator that $\dot{m}_{\text{CO}}$ is the parameter that increases the fastest, and therefore, that there is not enough oxygen to combust all the available fuel. According to Tewarson's research, a wood-crib fire becomes ventilation-controlled when the ratio $\dot{m}_{\text{CO}}/\dot{m}_{\text{CO}_2} > 0.036$ [26]. Ingason [26] proposed the following equation for $\dot{m}_{\text{CO}}/\dot{m}_{\text{CO}_2}$:

$$\frac{\dot{m}_{\text{CO}}}{\dot{m}_{\text{CO}_2}} = \frac{M_{\text{CO}} X_{\text{CO}}}{M_{\text{CO}_2} X_{\text{CO}_2}} = 0.636 \frac{X_{\text{CO}}}{X_{\text{CO}_2}} \quad (1)$$

where X is the volume concentration (or mole fraction) and M is the molecular weight (M is 28 g/mol for CO and 44 g/mol for CO₂).

Therefore, according to Relationship (1), when the wood crib combustion is ventilation-controlled, the following can be deduced:

$$X_{\text{CO}}/X_{\text{CO}_2} > 0.057 \quad (2)$$

3. Experimental Apparatus and Conditions

3.1. Reduced-Scale Tunnel Model

In this study, a multi-functional angular ventilation network fire simulation experiment platform was designed at a 1:14 ratio in relation to a physical roadway, as shown in Figures 1 and 2. The main body of the tunnel consisted of 11 cuboids with a cross-section of 30 × 30 cm, with a fire source branch length of 5 m and an inclination of 12°. One sidewall of the fire source branch was composed of 10 pieces of fire-resistant glass so that experimental phenomena could be observed. A total of 6 air-doors were installed in the experimental system to change the system composition and seal the tunnel. During the test, only the air-door at the branch of the fire source was opened to form a single tunnel. The fire source was set 1.175 m from the exit of the tunnel. Ten sets of K-type armored thermocouple trees were set below the ceiling of the fire source branch. Each thermocouple tree consisted of three thermocouples, which were 2 cm, 10.5 cm, and 19 cm away from the ceiling, and the group spacing was about 45 cm. Its measurement range was 1000 °C. A wind speed transmitter and a gas detector were installed in the air inlet section and the smoke exhaust section to measure the test wind speed and smoke concentration (CO₂, CO, and O₂). A KV621P two-way wind velocity transmitter was used to measure wind velocity in which the measurement range was −5~5 m/s, the measurement accuracy was 3% F.S, and the display resolution was 0.01. The gas detector used was an SGA-500B fixed gas sensor, which had a carbon monoxide detection range of 0~5000 ppm, a carbon dioxide detection range of 0~20,000 ppm, and an oxygen detection range of 0~30% VOL.

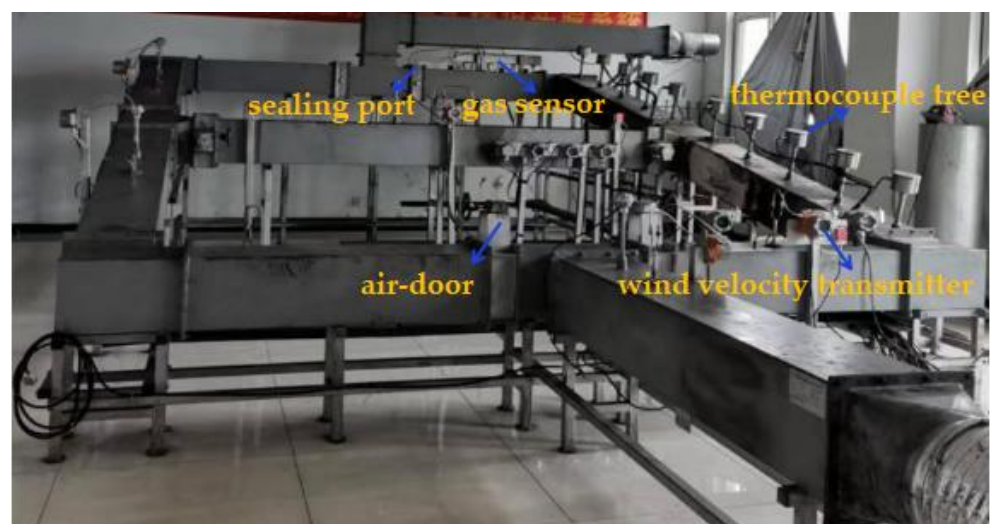


Figure 1. Experimental system.

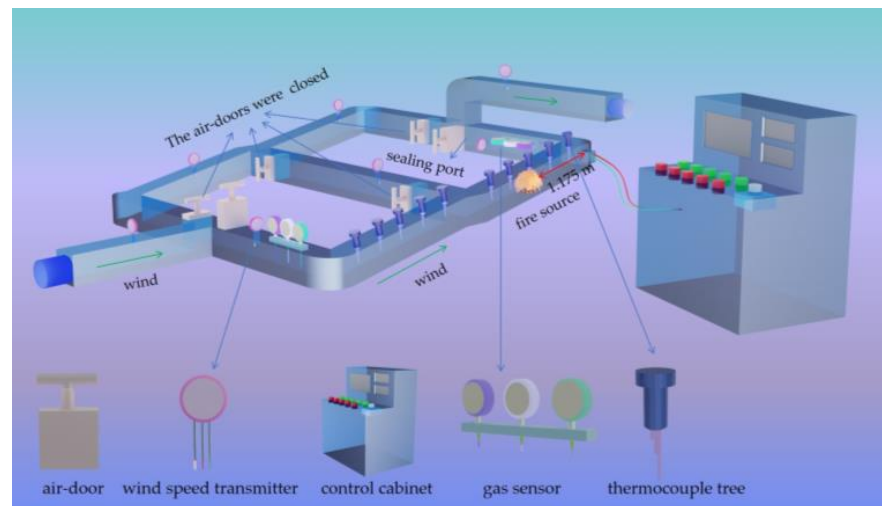


Figure 2. Diagram of test equipment.

3.2. Experimental Conditions

The test was set to seal at the tunnel exit. Before the experiment, the wood crib was cut into regular 25 cm strips that were 3 cm wide and 2 cm high. In total, 50 wood strips were selected for each working condition, with 10 layers, 5 wood strips per layer, and 1.5 cm of spacing between adjacent wood strips. The wood crib weighed about 3.2 kg.

In order to determine the initial time of the sealing measurement, an unsealed control group test was carried out first. The wind speed was set to 0.10 m/s, and the wood crib took 24 min to progress from ignition to flame-extinguishing. First, the combustion type of the wood crib was determined when the wind speed was 0.10 m/s. According to Equation (2), the volume fraction of CO on the downwind side of the fire source was divided by the volume fraction of CO₂, and the change in the X_{CO}/X_{CO2} ratio during the combustion of the wood crib was obtained, as shown in Figure 3.

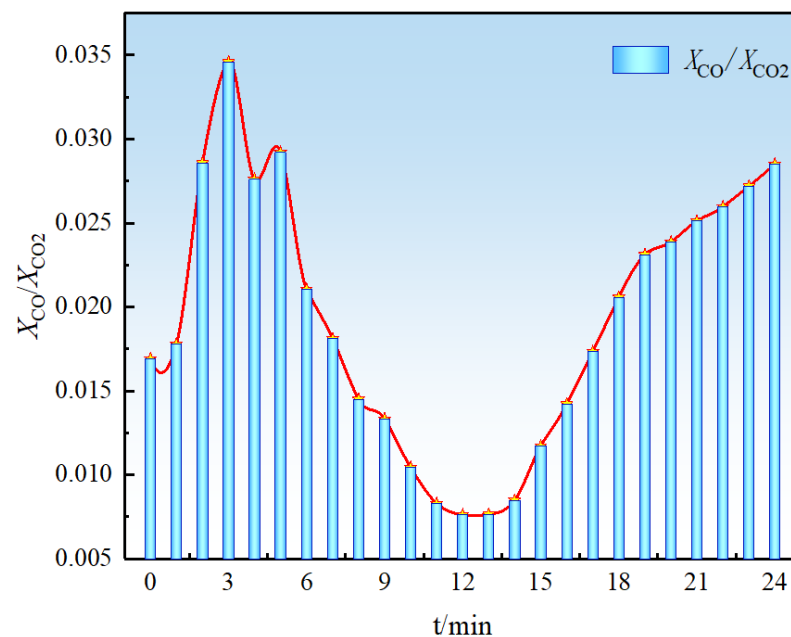


Figure 3. Variations in the ratio of X_{CO}/X_{CO2} on the downwind side of the fire.

It can be seen from Figure 3 that the ratio of X_{CO}/X_{CO2} on the downwind side of the fire source is always lower than 0.057 during the whole process of wood crib combustion.

Therefore, when the wind speed is 0.10 m/s, the wood crib combustion type is fuel-controlled combustion.

According to the average temperature change in smoke 1 m downwind of the fire source, the development trend in the fire is divided into three stages: the initial growth stage of the fire, the full development stage of the fire, and the fire attenuation stage [27]. As shown in Figure 4, after igniting the wooden stack for 2 min, the entire stack is completely on fire, and the wood stack enters the fully developed stage of fire at 2 min of combustion. The temperature reaches its peak at 8 min of combustion, which is the most intense moment during combustion. After burning for 12 min, the wood crib combustion enters the attenuation stage. According to the above analysis, 1 min, 3 min, 7 min, and 10 min after ignition were selected as the initial sealing times. The experimental conditions are shown in Table 1.

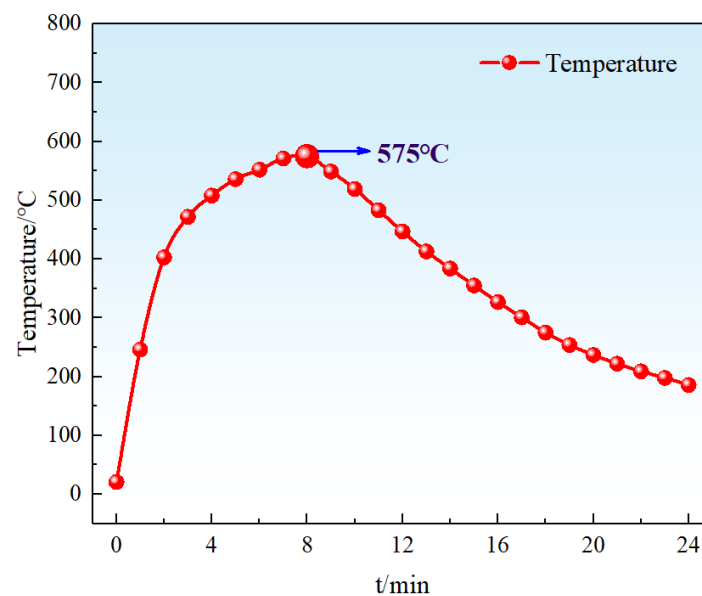


Figure 4. Variations in average temperature at the 1 m downwind side of the fire.

Table 1. Experimental conditions.

Test No.	Initial Sealing Time/min	The Weight of the Wood Crib/kg
1	1	3.2
2	3	3.2
3	7	3.2
4	10	3.2

4. Results and Discussion

4.1. Flame Morphology

Figure 5 presents the variations in flame morphology without sealing. It can be seen from Figure 5 that after the stack is ignited, the flame and high-temperature smoke flow rise along the oblique rear of the fire source under the action of the chimney effect and fresh air flow. Due to the release of heat after the combustion of wood cribs, the temperature increases, and the thermal decomposition rate will also accelerate. With time, the thermal decomposition rate will become faster and faster, resulting in more combustibles added to the fire, forming a larger range of flames along the downwind side of the inclined tunnel. As shown in Figure 5, the spread of flames in the full development stage of the fire is greater than that in the fire's initial growth stage.

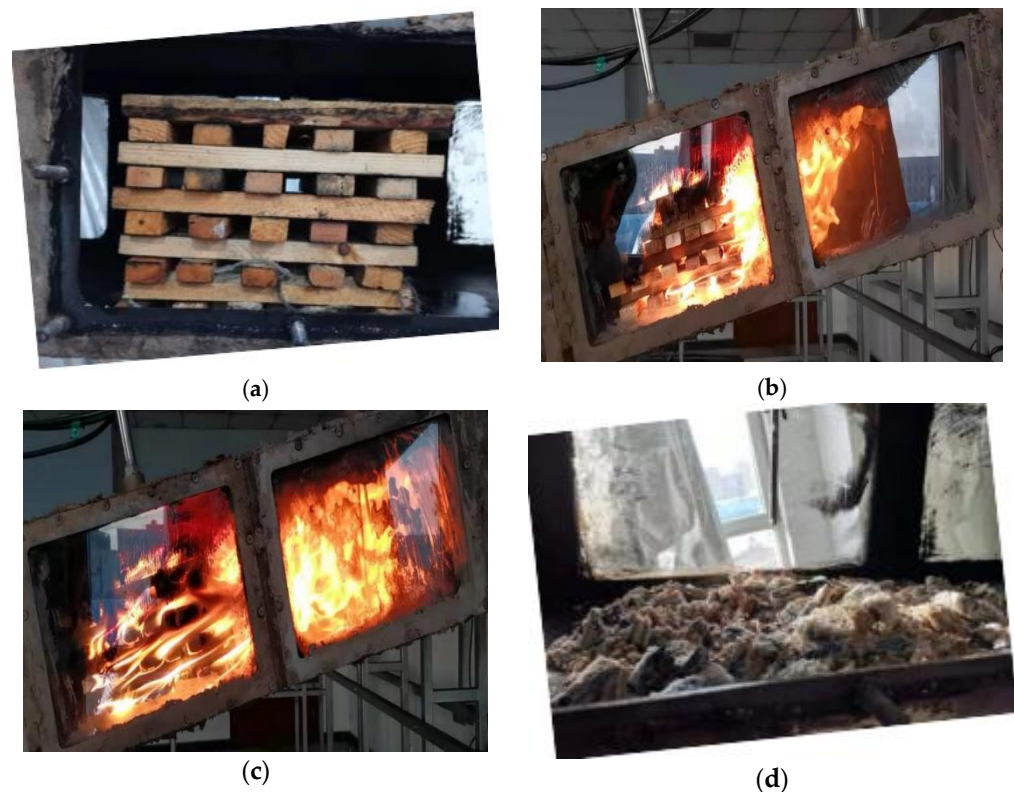


Figure 5. Variations in flame morphology without sealing: (a) before ignition; (b) initial stage of the fire; (c) full development stage of the fire; (d) after extinguishing.

With the thermal decomposition of wood cribs, a large amount of combustible gas is produced, stable flame combustion occurs, and the flame length remains basically unchanged. During this process, the stack gradually collapses due to the increased degree of carbonization, which damages its stability. When the combustible gas produced by the decomposition of wood cribs decreases, the flaming combustion gradually weakens, and oxygen begins to spread to the carbonaceous surface for combustion; when the combustible gas is not completely released, it is completely converted into flameless combustion until it is extinguished. As shown in Figure 5d, the ash content of the wood crib after combustion is gray–white, indicating that the wood crib is completely burned.

Figure 6 shows the change in flame morphology before and after sealing when the sealing time is 1 min. The combustion of the wood cribs before sealing is in the initial growth stage of the fire, and it can be observed that some of the wood cribs are still not completely burned, as shown in Figure 6. The combustible volatiles decomposed from the wood cribs burn to form a dark red flame, and this flame spreads along the downwind side of the fire source. At the moment of sealing, the influence of the air flow on the flame combustion pattern is weakened. The flame inclination angle decreases, and the angle between the flame and the ground is almost vertical. The fire plume reaches the ceiling directly, forming a ceiling jet and releasing some black smoke. This indicates that the wood crib is not yet fully burned. Because sealing reduces the amount of oxygen entering the tunnel, the fire becomes smaller and smaller. The flame on the wood crib back in the direction of the wind is extinguished first due to oxygen depletion, as shown in Figure 6c. The wood crib on the windward side continues to burn, but the combustion intensity becomes increasingly small until the oxygen content is insufficient to maintain combustion and the flame is extinguished. In Figure 6d, it can be seen that after the flame is extinguished, there are still some wooden cribs that have not entered the carbonization stage.

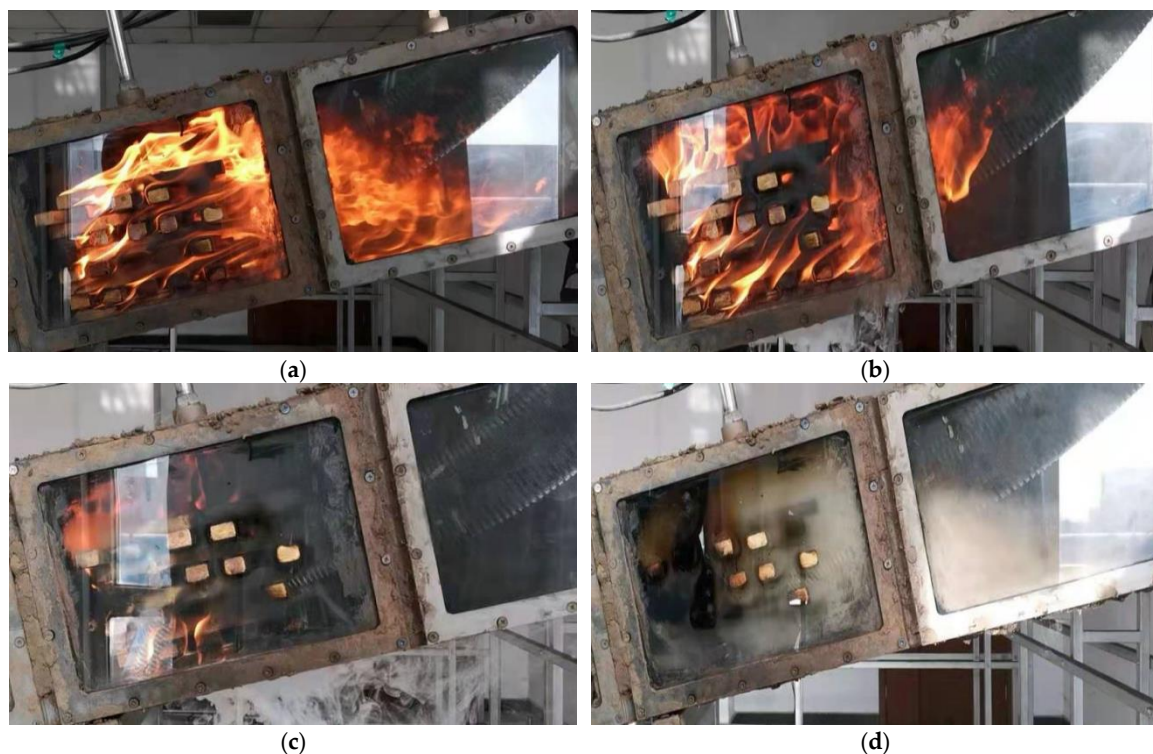


Figure 6. Variations in flame morphology before and after sealing at 1 min: (a) before sealing; (b) transient change after sealing; (c) shift to the left side of wood; (d) after extinguishing.

Figure 7 displays the change in flame morphology before and after sealing when the sealing time is 3 min. It can be seen from Figure 7 that before sealing, the oxygen content in the tunnel is sufficient, the whole wooden crib is carbonized and fully burned, and a dark red flame is formed. When the tunnel exit is sealed, a ceiling jet flame is formed above the fire source, and more black smoke is released. Then, the fire in the tunnel enters a ventilation-controlled combustion state. As shown in Figure 7c, after the closure, the fire on the downwind side of the wood crib was extinguished, and some wood cribs on the upwind side continued to burn to produce flames. This is because the tunnel exit is sealed, and the flue gas cannot be discharged. The flue gas first accumulates on the downwind side of the flame, the amount of oxygen decreases, and the flame on the downwind side of the wood crib is extinguished first. With the spread of smoke in the fire source area and continuous combustion, the amount of oxygen in the tunnel continues to decrease, and the flame on the wind side of the fire source is extinguished. From Figure 7d, it can be seen that when the flame is extinguished, the surface of the wood crib is basically black carbon.

Figures 8 and 9 present the changes in flame morphology before and after sealing when the sealing time is 7 min and 10 min, respectively. It can be seen from Figures 8 and 9 that when the sealing time is 7 min and 10 min, the combustion of the wood crib is in the full development stage before sealing. The decomposition of the wood crib produces a large volume of flammable volatiles which co-combust with the surface of the wood crib to form a bright flame. The fire and length of the flame along the downwind side of the roadway are relatively stable. During sealing, due to the large volume of flammable volatiles around the fire source, the flammable volatiles need to spread a longer distance under the ceiling to obtain enough oxygen to support the combustion of the remaining flammable volatiles. As shown in Figures 8c and 9c, the ceiling jet flame formed above the fire source extends to both sides of the ceiling and is longer and stronger than under the other two conditions. At the same time, a large amount of black smoke is released. The fire gradually becomes smaller and remains stable after dropping below a certain intensity. With the consumption of oxygen, the fire continues to decrease until it is extinguished.

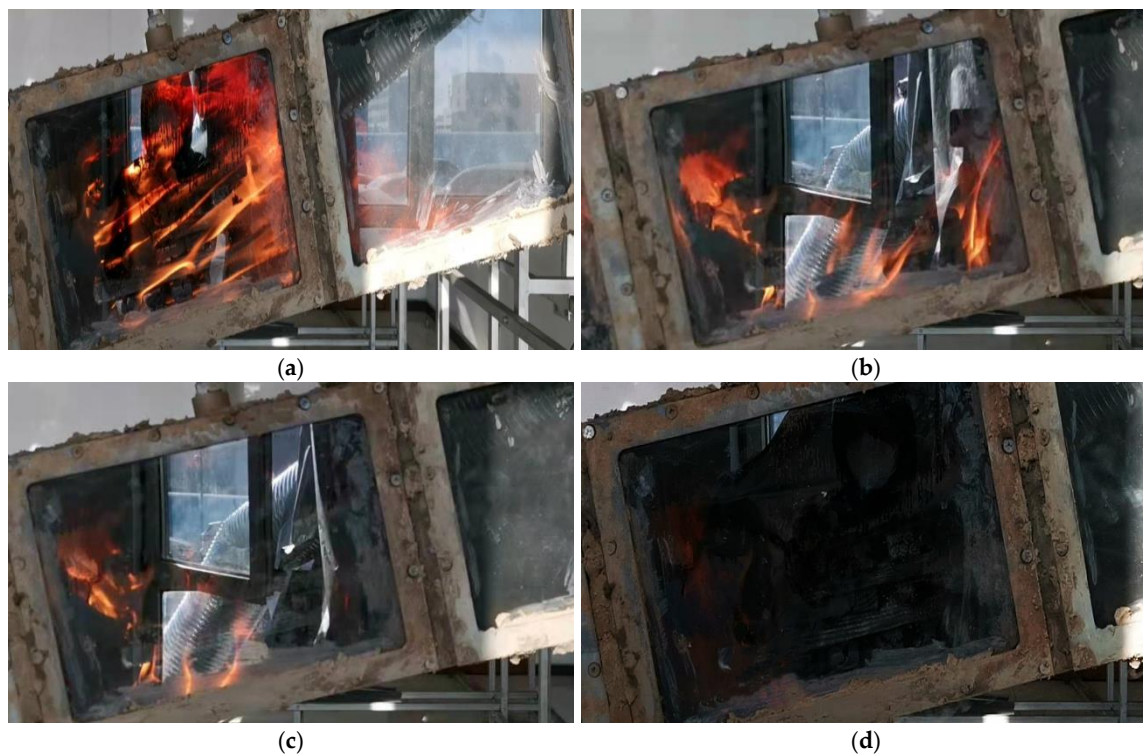


Figure 7. Variations in flame morphology before and after sealing at 3 min: (a) before sealing; (b) transient change after sealing; (c) shift to the left side of wood; (d) after extinguishing.

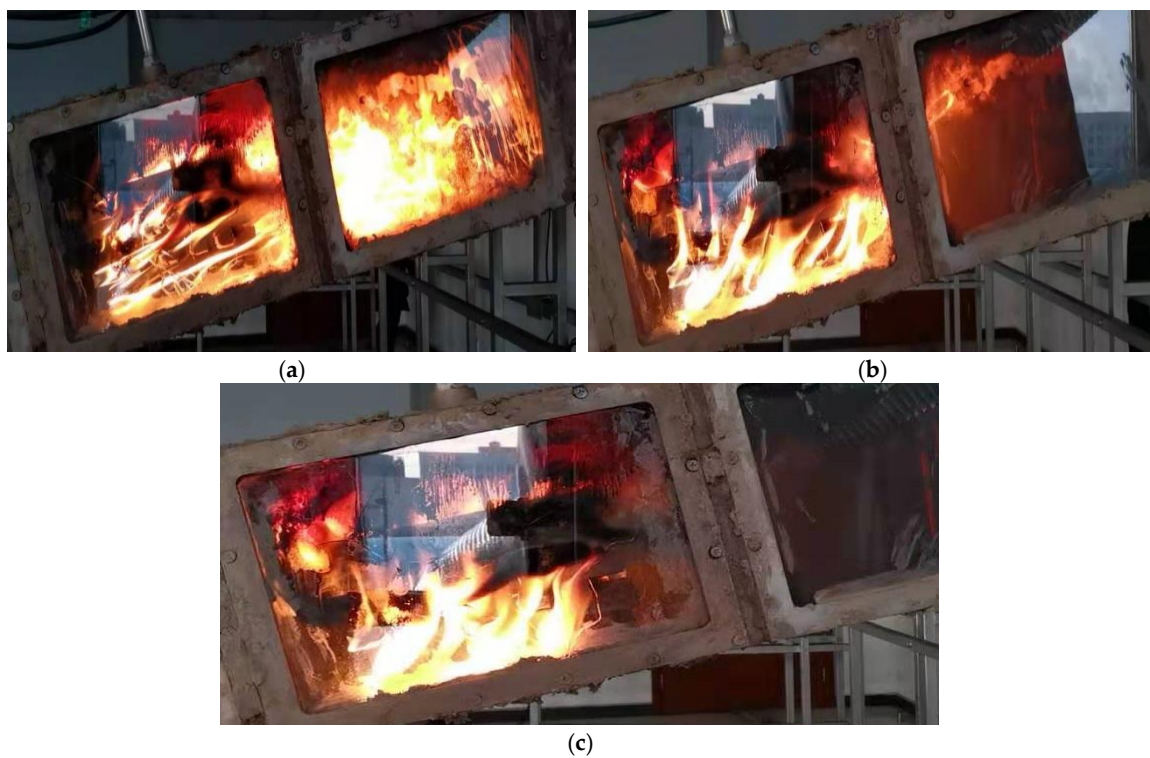


Figure 8. Variations in flame morphology before and after sealing at 7 min: (a) before sealing; (b) transient change after sealing; (c) steady-state combustion.

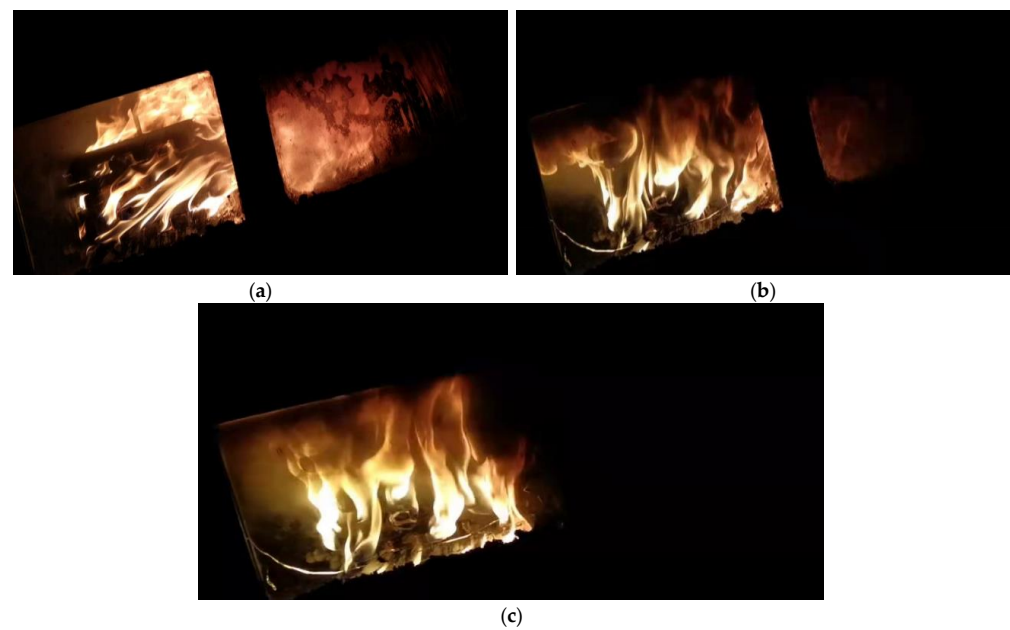


Figure 9. Variations in flame morphology before and after sealing at 10 min: (a) before sealing; (b) transient change after sealing; (c) steady-state combustion.

4.2. Gas Variation

Figure 10 displays the variation in the X_{CO}/X_{CO_2} ratio on the downwind side of the fire source at different sealing times. It can be seen from Figure 10 that the ratio of X_{CO}/X_{CO_2} on the downwind side of the fire source at different sealing times increases rapidly after sealing. This is because after the tunnel is closed, there is no fresh air supplement, the oxygen content is not sufficient, and the rate of CO produced by the wood crib combustion per unit of time is greater than the rate of CO_2 . Figure 10 shows that the ratio of X_{CO}/X_{CO_2} is greater than 0.057 1 min after sealing the tunnel exit at different times. Combined with Relationship (2), it can be seen that the combustion of the wood crib is changed from fuel-controlled to ventilation-controlled. When the wood crib burns more fully (7 min and 10 min), the rate increase of the X_{CO}/X_{CO_2} ratio is significantly faster than at other sealing times (1 min and 3 min). When the initial sealing time is 10 min, the X_{CO}/X_{CO_2} ratio increases from 0.007 to 0.435 1 min after sealing, signifying an increase of 0.428. While the initial sealing time is 1 min, the X_{CO}/X_{CO_2} ratio increases from 0.047 to 0.210 1 min after sealing, signifying an increase of 0.163.

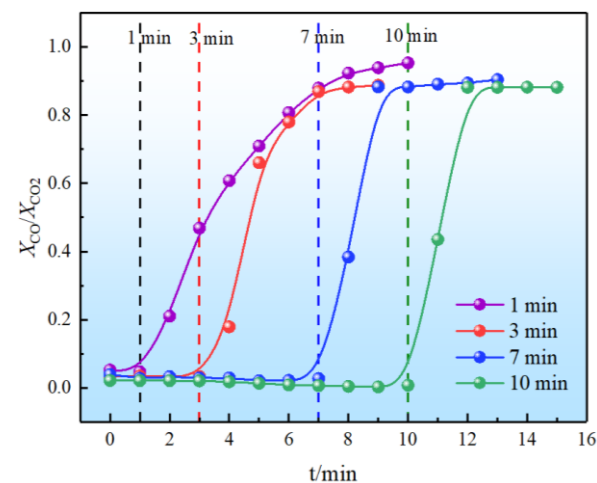


Figure 10. Variations in the ratio of X_{co}/X_{CO_2} on the downwind side of the fire at different sealing times.

4.3. Longitudinal Temperature Distribution

Figure 11 shows the longitudinal temperature distribution beneath the tunnel ceiling under different initial sealing times. It can be seen that before sealing, the later the sealing time, the more fully the wood crib burns, and the higher the peak temperature, as shown in Figure 11. The maximum temperature of the ceiling appeared at 0.50 m from the downwind side of the fire source. This is due to the effects of wind speed and the chimney effect, which cause the flame to tilt towards the downwind side of the fire source. Additionally, the high-temperature area caused by flame thermal radiation also shifts, resulting in a high temperature at 0.50 m on the downwind side of the fire source.

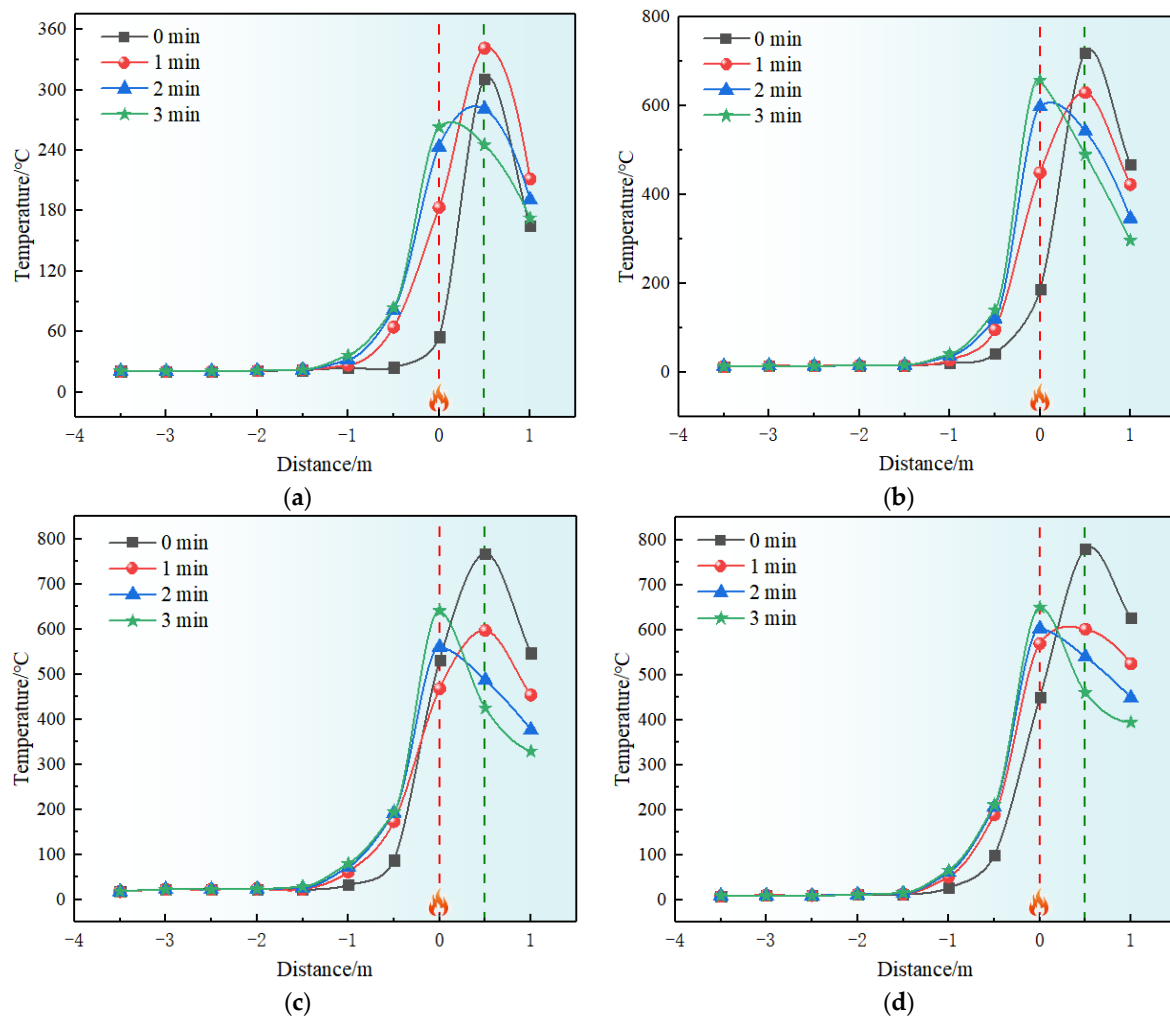


Figure 11. Longitudinal distribution of ceiling temperature within three minutes of sealing: (a) 1 min; (b) 3 min; (c) 7 min; (d) 10 min.

Figure 11 shows that the maximum temperature of the ceiling after sealing is lower than that before sealing. However, when the sealing time is 1 min, the maximum temperature of the ceiling 1 min after sealing is higher than that before sealing (0 min). This is because 1 min is the initial growth stage of the fire, and the overall temperature of the wood stack is relatively low, with most areas of the wood stack in the dry stage. At this time, the tunnel exit is closed and the flame is concentrated at the fire source, which makes the combustion rate of the wood crib increase to a certain extent, and the temperature at the fire source increases. However, the combustion of wood cribs still requires the absorption of external heat to accelerate the pyrolysis rate. Due to the reduction in oxygen supply, the combustion process is inhibited, the flame begins to extinguish, and the temperature gradually decreases.

Figure 11 demonstrates that the influence of different sealing times on the longitudinal distribution of the tunnel ceiling temperature is basically the same. In the third minute after the tunnel exit is sealed at different initial times, the highest temperature point appears at the center of the ceiling. For example, when the initial sealing time is 3 min, before the sealing, the temperature at the fire source is 187 °C, and the temperature is 720 °C at 0.50 m on the downwind side of the fire source. At 3 min after sealing, the temperature at the fire source was 658 °C, and the temperature at 0.50 m on the downwind side of the fire source was 490 °C. This is because sealing effectively blocks the airflow from entering the test tunnel, reducing the flame inclination angle and making the flame orientation approximately vertical.

After sealing, within 2 min, as the sealing time increases, the temperature at 0–1 m on the windward side of the fire source increases. This is because after sealing, the wind speed decreases, the flame inclination angle decreases, and the heat radiation of the fire plume causes the temperature measurement point to heat up. On the other hand, after the tunnel is sealed, some of the smoke flows towards the upwind side of the fire source. After sealing for 2 to 3 min, the flame combustion state is relatively stable, and the temperature increase on the windward side of the fire source from 0 to 1 m is not significant. Due to the sealing, although a small part of the countercurrent smoke flow travels in the opposite direction to the inlet air flow, most of the high-temperature smoke flows to the downwind side. A large amount of heat moves towards the downwind side, and the temperature at each temperature measurement point on the downwind side of the fire source is higher than the corresponding temperature measurement point on the upwind side.

4.4. Smoke Temperature Variation

Figure 12 displays the average temperature variation at 1 m on the downwind side of the fire source versus different initial sealing times. It can be seen from Figure 12 that after sealing, with an increase in time, the average temperature at 1 m on the downwind side of the fire source shows an exponential decay trend. This is because sealing limits the supply of fresh air in the external environment. The flame can only entrain the limited oxygen on the downwind side to support combustion, which causes the oxygen concentration near the fire source to decrease rapidly. When the oxygen concentration is reduced to a level that cannot support the complete combustion of the wood crib, the intensity of the wood crib combustion and the heat released decrease, and the average temperature of the downwind side of the fire source decreases accordingly.

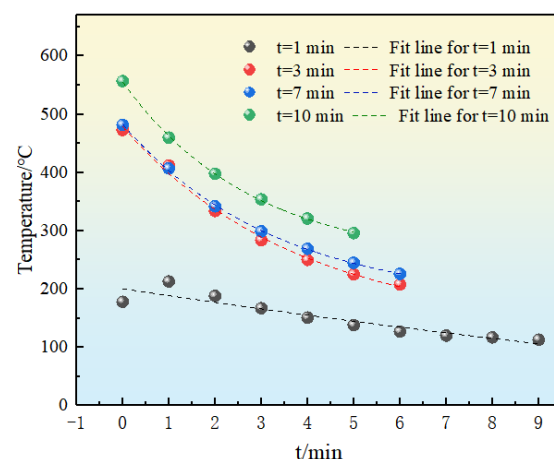


Figure 12. Variations in average temperature at the 1 m downwind side of the fire source at different sealing times.

An exponential function is used to fit the data, which satisfies the relationship $T(t) = k_1 + k_2 e^{-t/k_3}$. In this formula, k_1 , k_2 , and k_3 are fitting coefficients. The fitting results at different

sealing times are shown in Table 2. According to Table 2, except for the sealing time of 1 min, the correlation coefficients are generally above 0.99, indicating good fitting results.

Table 2. Fitting equation for the downwind side of the fire source.

Sealing Time/min	T(t)	R ²
1	$-177.0 + 377.5e^{-t/31.2}$	0.865
3	$133.7 + 345.3e^{-t/3.8}$	0.996
7	$175.7 + 307.5e^{-t/3.3}$	0.999
10	$245.5 + 310.3e^{-t/2.8}$	0.999

5. Conclusions

Using a reduced-scale tunnel model, the influence of sealing time on the combustion process of wooden cribs was experimentally studied. Several conclusions can be reached:

1. After sealing, the flame orientation is approximately vertical, and a ceiling jet flame is formed in the tunnel. The maximum temperature of the ceiling is offset towards the fire source. The later the sealing time, the more prominent the ceiling jet flame is. When the sealing time is 1 min and 3 min, combustion can be suppressed with a relatively shorter burning duration. When the sealing time is 1 min, there are still some wood cribs that are not carbonized after combustion.
2. After sealing the tunnel exit at different times, the ratio of X_{CO}/X_{CO2} on the downwind side of the fire source first increases rapidly; as the sealing time increases, the X_{CO}/X_{CO2} ratio increases more rapidly in a short period of time. The combustion of the wood crib is transformed from fuel-controlled to ventilation-controlled.
3. The average temperature at 1 m on the downwind side of the fire source has an exponential decay relationship with time. Sealing at 3 min, 7 min, and 10 min results in a decrease in the maximum temperature of the tunnel ceiling. Sealing at 1 min demonstrates that after sealing, the flames concentrate at the source of the fire, causing the combustion rate of the wood crib to increase to a certain extent, and the temperature of the tunnel ceiling increases suddenly. In the process of tunnel sealing, certain cooling measures should be taken to improve the sealing effect.

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References

1. Han, J.Q. Study on the Fire Smoke Spreading Characteristics in the Tunnel with One Closed End. Ph.D. Thesis, Chongqing University, Chongqing, China, 2022.
2. Zhao, P.; Chen, T.; Yuan, Z.; Xie, Y.Y.; Yu, N.Y. Critical shaft height for complete smoke exhaustion during fire at the worst longitudinal fire location in tunnels with natural ventilation. *Fire Safety J.* **2020**, *116*, 103207. [[CrossRef](#)]

3. Li, C.H. Experimental Study on Smoke Temperature and Flow Characteristics of Tunnel Fire during Sealing. Master's Thesis, Xi'an University of Science and Technology, Xi'an, China, 2020.
4. Chen, J.F.; Cheng, H.H.; Wei, X.; Wen, Q.W.; Wu, L.; Liu, C.; Zhong, M.H. Temperature measurement errors in full scale tunnel fire experiments. *Tsinghua Sci. Technol.* **2022**, *62*, 1618–1625.
5. Li, L.M.; Li, S.; Wang, X.G.; Zhang, H.P. Fire induced flow temperature along tunnels with longitudinal ventilation. *Tunn. Undergr. Space Technol.* **2012**, *32*, 44–51. [[CrossRef](#)]
6. Liu, F.; Yu, L.X.; Weng, M.C.; Lu, X.L. Study on longitudinal temperature distribution of fire induced ceiling flow in tunnels with different sectional coefficients. *Tunn. Undergr. Space Technol.* **2016**, *54*, 49–60. [[CrossRef](#)]
7. Kang, K. Characteristic length scale of critical ventilation velocity in tunnel smoke control. *Tunn. Undergr. Space Technol.* **2010**, *25*, 205–211. [[CrossRef](#)]
8. Liu, C.; Zhong, M.H.; Tian, X.; Zhang, P.H.; Li, S.W. Study on emergency ventilation for train fire environment in metro interchange tunnel. *Build Environ.* **2019**, *147*, 267–283. [[CrossRef](#)]
9. Yao, Y.Z.; Wang, Y.T.; Chen, L.; Ren, F.; Shi, C.L. Numerical study on coupled smoke control using longitudinal ventilation and naturally ventilated shafts during fires in a road tunnel. *Fire* **2023**, *6*, 126. [[CrossRef](#)]
10. Liang, Q.; Li, Y.F.; Li, J.M.; Xu, H.; Li, K.Y. Numerical studies on the smoke control by water mist screens with transverse ventilation in tunnel fires. *Tunn. Undergr. Space Technol.* **2017**, *64*, 177–183. [[CrossRef](#)]
11. Gong, L.Y.; Peng, Y.F.; Xu, J.; Li, W.L.; Jia, T.Y.; Ma, J.Q.; Li, H.H. Effect of Semi-Transverse Ventilation Velocity on Combustion Characteristics of Pool Fire Sources in a Scaled Tunnel. *Fire* **2024**, *7*, 18. [[CrossRef](#)]
12. Chow, W.K.; Wong, K.Y.; Chung, W.Y. Longitudinal ventilation for smoke control in a tilted tunnel by scale modeling. *Tunn. Undergr. Space Technol.* **2010**, *25*, 122–128. [[CrossRef](#)]
13. Li, Y.Z.; Lei, B.; Ingason, H. The maximum temperature of buoyancy-driven smoke flow beneath the ceiling in tunnel fires. *Fire Safety J.* **2011**, *46*, 204–210. [[CrossRef](#)]
14. Hu, L.H.; Huo, R.; Wang, H.B.; Li, Y.Z.; Yang, R.X. Experimental studies on fire-induced buoyant smoke temperature distribution along tunnel ceiling. *Build Environ.* **2007**, *42*, 3905–3915. [[CrossRef](#)]
15. Zhao, P.; Yuan, Z.; Yu, N.; Liang, C.C. Effect of heat release rate and exhaust vent settings on the occurrence of plug-holing during tunnel fires with two-point extraction ventilation. *Tunn. Undergr. Space Technol.* **2020**, *106*, 103617. [[CrossRef](#)]
16. Ma, L.; Li, C.H.; Zhang, P.Y.; Qiu, X.Z.; Zhao, X. Influence of sealing ratio on ceiling temperature distribution of tunnel fire. *China Safety Sci. J.* **2020**, *30*, 79–85.
17. Yao, Y.Z.; He, K.; Peng, M.; Shi, L.; Zhang, H.P. Maximum gas temperature rise beneath the ceiling in a portals sealed tunnel fire. *Tunn. Undergr. Space Technol.* **2018**, *80*, 10–15. [[CrossRef](#)]
18. Chen, C.K.; Xiao, H.; Wang, N.N.; Shi, C.L.; Zhu, C.X.; Liu, X.Y. Experimental investigation of pool fire behavior to different tunnel-end ventilation opening areas by sealing. *Tunn. Undergr. Space Technol.* **2017**, *63*, 106–117. [[CrossRef](#)]
19. Ma, L.; Zhang, P.Y.; Guo, R.Z. GA-SVM model for prediction flue gas temperature of roadway fire under sealing process. *J. China Univ. Min. Technol.* **2021**, *50*, 641–648.
20. Huang, Y.; Li, Y.; Dong, B.; Li, J.M.; Liang, Q. Numerical investigation on the maximum ceiling temperature and longitudinal decay in a sealing tunnel fire. *Tunn. Undergr. Space Technol.* **2018**, *72*, 120–130. [[CrossRef](#)]
21. Fernandez, A.F.; Maria, C.A. Analysis of the fire propagation in a sublevel coal mine. *Energies* **2020**, *13*, 3754. [[CrossRef](#)]
22. Yao, Y.Z.; Cheng, X.D.; Shi, L.; Zhang, S.G.; He, K.; Peng, M.; Zhang, H.P. Experimental study on the effects of initial sealing time on fire behaviors in channel fires. *Int. J. Therm. Sci.* **2018**, *125*, 273–282. [[CrossRef](#)]
23. Yao, Y.Z. Fire Behaviors and Smoke Transportation Law of Tunnel Fires under Confined Portal Boundaries. Ph.D. Thesis, University of Science and Technology of China, Hefei, China, 2019.
24. Hu, L.H.; Huo, R.; Wang, H.B.; Li, Y.Z.; Lu, Q.; Yang, L.Z. Judgement on critical burning state of wood crib from ventilation to fuel controlled regime by concentration of carbon monoxide in combustion products. *J. Combust. Sci. Technol.* **2004**, *4*, 371–374.
25. Zhu, W.; Liao, G.X.; Lu, P.; Li, P.D.; Hung, Y.X. Combustion Process under Longitudinal Ventilation in Tunnel Using Wood Crib Fire. *J. Combust. Sci. Technol.* **2006**, *1*, 71–75.
26. Ingason, H.; Li, Y.Z.; Lönnemar, A. *Tunnel Fire Dynamics*, 2nd ed.; Springer: Gewerbestrasse, Switzerland, 2015; pp. 23–43.
27. MA, L.; Zhang, P.Y.; Li, C.H.; Liu, S. Prediction model of roadway fire temperature field under different plugging conditions. *J. Xi'an Univ. Sci. Technol.* **2021**, *41*, 213–219.

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