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EXPERIMENTAL STUDY ON THE SMOKE SPREADING CHARACTERISTICS OF FIRE IN THE MERGING SECTION OF THE ARCH BIFURCATION TUNNEL

Yunxiao Xin[1], Yaqiong Wang [2]

Abstract: Branching tunnels are a crucial component of underground transportation networks, and their structural shape results in a more complex distribution of wind flow fields in the bifurcated section compared to normal tunnels. Especially, the arch tunnels have a sudden change of cross-section at the bifurcation point, which makes it more difficult to control the spread of smoke in the tunnel at the bifurcation. This paper takes the Dapeng Tunnel of the Shenzhen Outer Ring Expressway as the research object, and studies the fire smoke spreading rule for the merging section of the arch bifurcation tunnel through model experiments. The results show that when the fire source is located in the normal section, the critical wind speed is higher than that of a normal tunnel, and smoke backflow is more likely to occur upstream of the fire source. When the fire source is located in the transition section of the tunnel, smoke tends to accumulate in this section during the spread process and form a long backflow upstream of the fire source. When the fire source is located in the transition section, the critical wind speed is essentially the same as that of a normal tunnel, and smoke tends to accumulate and flow back into the non-fire source bifurcation section in the tunnel transition section. In the transition section of the tunnel, smoke tends to fluctuations at the tunnel roof and eddies at the side walls of the transition section. By increasing the wind speed at the entrance of the main tunnel and ramp, it is possible to significantly suppress smoke backflow and reduce temperature, thereby effectively controlling the scale of the tunnel fire.

Keywords: Bifurcated tunnel, Arched section, Fire ventilation, Smoke spread, Model experiment

1. INTRODUCTION

As a closed and narrow underground space, the structural characteristics of tunnels can cause fires to spread quickly and complicate evacuation and rescue, posing serious challenges to tunnel operation safety. With the development of underground transportation networks, the application of bifurcation tunnels in urban tunnels has become increasingly widespread. The merging point formed by the connection between the ramp and the main road in a branching tunnel can cause serious interference to the ventilation and smoke exhaust inside the tunnel. At the same time, vehicles near the branching point are susceptible to collision accidents due to factors such as obstructed visibility and lane changes (Wang et al., 2014). Therefore, it is necessary to study the diffusion law of fire smoke in bifurcation tunnels and develop reasonable smoke emission and control plans.

The adverse effects of tunnel fires mainly manifest as temperature and smoke diffusion. Kurioka et al. (2003) constructed a prediction model for the maximum temperature of the roof jet by conducting a series of scale tunnel fire model experiments on the distribution characteristics of fire temperature in tunnels. Through conducting inclined tunnel fire tests, Hu et al. (2013) found that the highest temperature at the top of inclined tunnels was significantly lower than that of horizontal tunnels, and constructed a temperature attenuation prediction model based on slope parameters. Yao et al. (2018) conducted small-scale experimental research on the impact of sealing at both ends of the tunnel on the maximum temperature rise and constructed a prediction model for the maximum temperature rise. Gao et al. (2021) conducted a study on the fire scenario of a comprehensive pipe gallery with one end closed, and systematically analyzed the distribution law of the highest temperature rise on the ceiling and

[1] Lecturer, Xin, Yunxiao, Ph.D. in Geological Engineering, Teacher, School of Highway, Chang'an University, Middle Section of Nan'er huan Road, Xi'an, China, hapoaaa@foxmail.com.
[2] Professor, Wang, Yaqiong, Ph.D. in Tunnel Engineering, Teacher, School of Highway, Chang'an University, Middle Section of Nan'er huan Road, Xi'an, China, ys08@gl.chd.edu.cn.

the characteristics of hot smoke flow. Huang et al. (2019, 2021) conducted fire tests on small-sized bifurcated tunnels under longitudinal ventilation and established segmented function-based maximum temperature prediction models and longitudinal temperature distribution models, respectively. Chen et al. (2020, 2023) conducted small-scale fire tests on bifurcation tunnels, analyzed the effect of ramp slope on the critical wind speed and maximum temperature rise response of the main tunnel, and constructed a roof maximum temperature rise prediction model based on slope parameters. Li et al. (2010) conducted experimental research on the smoke propagation law of tunnel fires in a 12-meter-long horizontal tunnel model, and proposed a calculation formula for the smoke reflux length of tunnel fires. Gao et al. (2022) conducted experimental research on inclined tunnel fires and found that as the slope of the tunnel increases, the highest temperature rise area at the top of the tunnel exhibits a clear downstream migration characteristic, and the increase in the highest smoke temperature demonstrates a decreasing trend. Lu et al. (2022a, 2022b) studied the effects of bifurcation angle and longitudinal position of the fire source on the temperature distribution at the top of a bifurcated tunnel fire through model experiments and numerical simulations, and constructed a prediction formula for the maximum temperature at the top of the tunnel to decay along the longitudinal direction. Li et al. (2021) studied the effect of the longitudinal position of the fire source on the maximum temperature of the ceiling using FDS, and found that under low longitudinal wind speed conditions, the maximum temperature of smoke in bifurcated tunnels was significantly lower than that in single point entry and exit tunnels, and the change in the longitudinal position of the fire source did not show a significant effect on the maximum temperature inside the tunnel. Lei et al. (2021) analyzed the influence of the location of the fire source on the longitudinal distribution characteristics of temperature in a bifurcated tunnel through physical model experiments, and found that when the fire source is located in the bifurcation area, the temperature of the smoke inside the tunnel is slightly lower than that when the fire source is far away from the bifurcation area.

Through a series of related studies on bifurcation tunnel fires, we have gained a certain understanding of the characteristics of smoke propagation in bifurcation tunnels and developed relevant smoke control plans. However, the existing research objects are mostly rectangular cross-section bifurcation tunnels, and the influencing parameters of bifurcation tunnel structures are mostly focused on changes in bifurcation angles and ramp slopes. Unlike rectangular-section bifurcation tunnels, the cross-section of arched-section bifurcation tunnels undergoes a sudden change in the bifurcation transition section. Therefore, smoke tends to generate eddies at structural changes during the spreading process, which makes it easier for smoke to gather at bifurcation points, as shown in Figure 1. Meanwhile, the sudden change at the top makes it difficult for the upstream airflow to fully cover the entire space inside the tunnel, resulting in difficulty in suppressing the backflow of smoke at the top of the bifurcation transition section. Therefore, it is necessary to study the spread characteristics of fire smoke in arched section bifurcation tunnels under different bifurcation forms and fire source positions, and propose reasonable fire smoke exhaust plans.

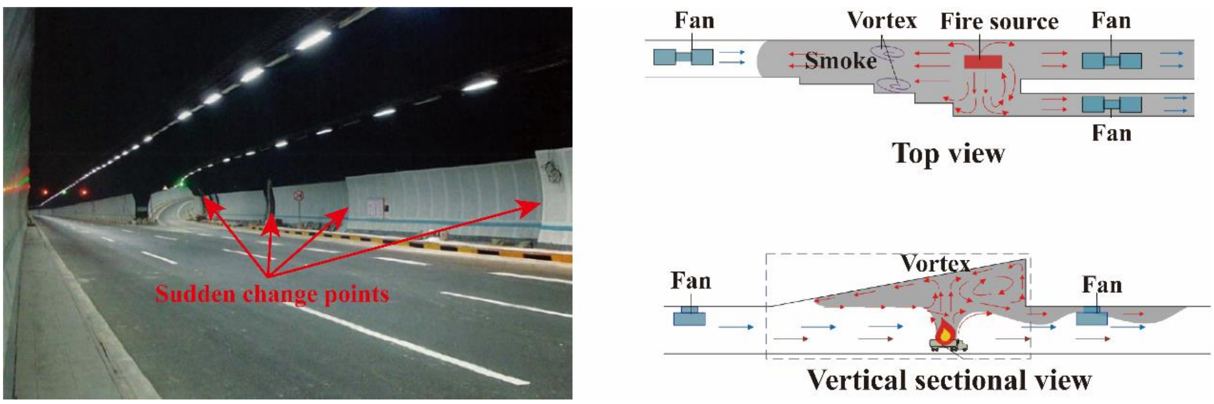

Figure 1. *The sudden change in cross-section of the arched bifurcation tunnel.*

2. MATERIAL AND METHODS

This article takes the bifurcation and merging area of the Shenzhen Dapeng Tunnel as the prototype to study the arch-shaped bifurcation tunnel. The direction of wind flow in the tunnel is consistent with the direction of traffic flow, with the main line of the tunnel consisting of 3 lanes and the branching area consisting of 2+2 lanes. According to the structural characteristics of the bifurcation tunnel, it can be divided into the normal section, transition section, main section, and branch section. The transition section is further divided into transition sections I-IV according to the size of the cross-section. The division of tunnel sections is shown in Figure 2. Due to the different impacts of fires occurring in different locations, this article sets the fire source at the centerline of the main section, branch section, and transition section III.

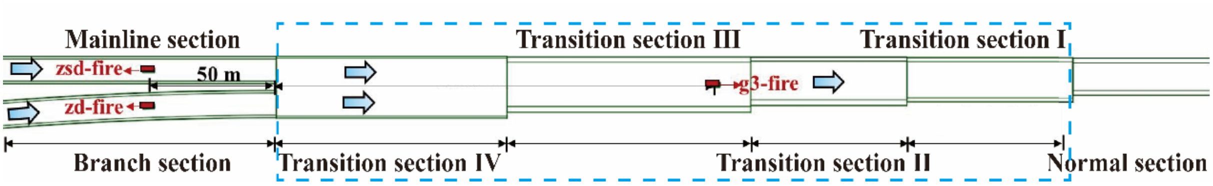

Figure 2. *Schematic diagram of tunnel physical model segments.*

To observe the actual effects of fire temperature and smoke diffusion in bifurcation tunnels, a physical experimental model with a similar scale of 1:12 was built for the merging section of the bifurcation tunnels. The model was simplified according to the principle of similarity and the characteristics of the tunnel prototype. The specific dimensions of the physical model are shown in Table 1. To resist the high temperature generated by fire tests, the main structure of the tunnel model is made of stainless-steel plates, and observation windows are set on the side walls for easy observation. The experimental model adopts a modular design and is assembled from multiple tunnel components. Each joint of the experimental model is sealed, and the layout effect of the model is shown in Figure 3. A set of temperature acquisition modules is installed every 1 meter in the model to collect the temperature inside the tunnel. At the same time, a laser with a power of 200 MW and a wavelength of 532 nm is selected to observe the diffusion pattern of smoke inside the tunnel.

Table 1. *Dimensional parameters of the tunnel model.*

Section	Lane number	Length(m)	Width(m)	Heigth(m)
Mainline	2	15	0.82	0.6
Branch	2	2	0.82	0.6
TransitionI	3	2	1.33	0.73
Transition II	3	2	1.46	0.82
Transition III	3	2	1.67	0.91
Transition IV	4	2	1.86	0.98

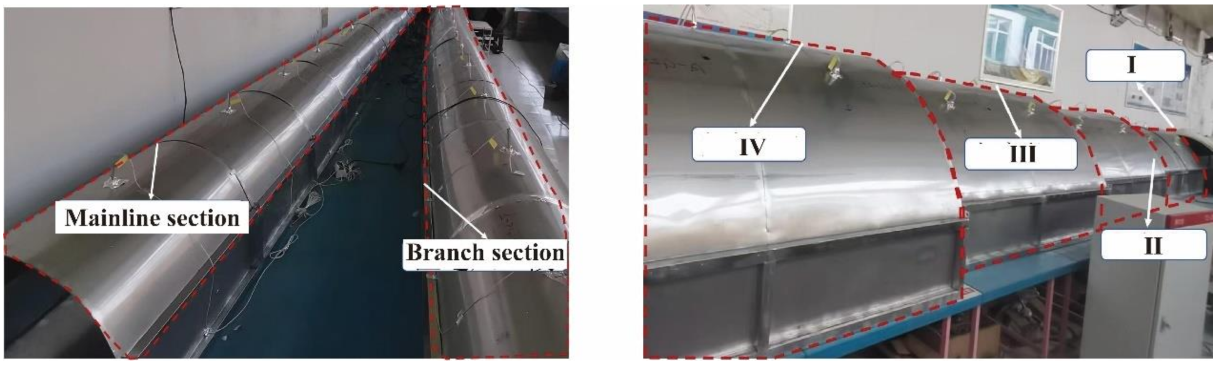

Figure 3. *Tunnel fire experiment model.*

Install variable frequency axial flow fans at the upstream center of the entrance section of the tunnel model to provide different wind speeds required for testing. The required wind speeds for the experiment are 0.43, 0.72, and 0.87 m/s, respectively, and their corresponding actual wind speeds are 1.5, 2.5, and 3.0 m/s. The actual heat release rate of the simulated tunnel fire source is 20 MW. According to the similarity criterion, the heat release rate of the model test fire source can be converted to 40.09 kW. The test fire source uses 99% anhydrous ethanol as fuel, supplemented by smoke cake as a smoke tracer substance. According to the heat calculation, when the size of the test tray is determined to be 27 × 35 cm and the height of the ethanol liquid surface is 1 cm, the corresponding heat release rate is 40.31 kW, which can meet the test requirements. The propagation characteristics of smoke generated by fire sources at different locations under different wind speed conditions can be obtained through physical model experiments.

3. RESULTS AND DISCUSSION

3.1. Smoke spread characteristics of mainline section fires

Figure 4 shows the flame and smoke propagation patterns at the entrance section of the main tunnel under different wind speed conditions when the fire source is located on the main section of the tunnel. The high-temperature smoke released by the combustion of the fire source rises due to the buoyancy effect of heat, forming vertical smoke. When the wind speed is 0.43 m/s, the inertia force of longitudinal ventilation is small, and the thermal buoyancy force plays a dominant role. The smoke impacts the top and spreads upstream and downstream of the fire source, resulting in smoke backflow. When the wind speed is 0.72 m/s, the inertial force gradually becomes dominant, and the smoke mainly spreads downstream. When the wind speed is 0.87 m/s, the inertial force increases significantly, and there is no obvious reverse flow of smoke, and the concentration of smoke decreases significantly. The above phenomenon indicates that as the longitudinal wind speed increases, the effect of the inertial force of the airflow gradually becomes higher than that of the thermal buoyancy force, and the phenomenon of smoke backflow continues to decrease.

Figure 4. *The spread of smoke from a fire in the mainline section.*

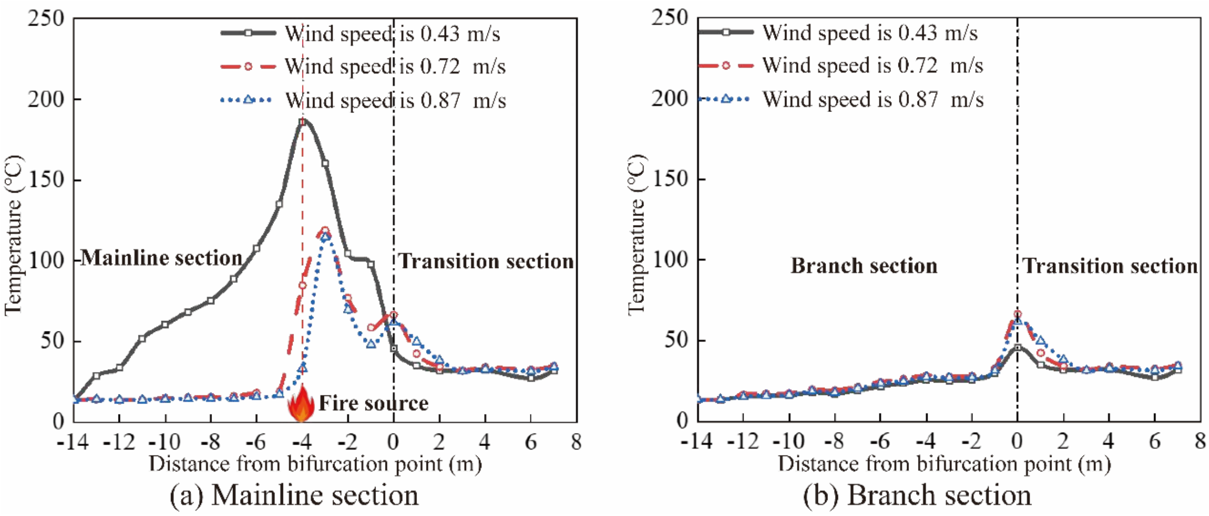

Figure 5. *Temperature distribution at the top of the tunnel under the fire in the mainline section.*

Figure 5 demonstrates the temperature distribution at the top of the tunnel under different wind speed conditions when the fire source is located on the main section of the tunnel. As the wind speed increases, the temperature near the fire source decreases significantly, and the location of the highest temperature gradually shifts downstream. The highest temperatures corresponding to wind speeds of 0.43, 0.72, and 0.87 m/s are 186.0, 118.9, and 114.5 °C, respectively. When the wind speed is 0.43 m/s, the temperature upstream of the fire source increases significantly, indicating a significant phenomenon of smoke backflow; When the wind speed increases to 0.72 m/s, the phenomenon of smoke backflow upstream of the fire source disappears; When the wind speed further increases to 0.87 m/s, there is no significant change in the temperature upstream of the fire source, and the smoke no longer flows back. When the smoke spreads to the transition section, since the cross-section of the transition section is 2.5 times that of the main section, the smoke disperses within the transition section, resulting in a significant decrease in temperature. As the wind speed increases, smoke can enter the transition section faster. The expansion of the cross-section will lead to a decrease in wind speed in the transition section, leading to smoke accumulating in the transition section. Therefore, the temperature in the transition section will increase slightly with an increase in tunnel wind speed. Under different wind speed conditions, the top temperature of the ramp side reaches its maximum value at the bifurcation point. This is because there is a structural change at the bifurcation point, with the height of the transition section IV being 0.98 m and the height of the branch section being 0.60 m. Smoke accumulates at the top of the transition section IV, leading to a significant increase in temperature at this point. Due to the low wind speed inside the ramp, the smoke accumulated in the transition section IV gradually flows back into the ramp, leading to the temperature at the top of the ramp to rise. Furthermore, as the wind speed increases, the smoke is brought into the transition section faster, leading to a sudden decrease in airflow velocity within the transition section. This accelerates the accumulation of smoke, leading to more smoke flowing into the ramp and exacerbating the backflow of smoke on the ramp. As a result, the temperature at the top of the ramp demonstrates an upward trend.

3.2. Smoke spread characteristics of branch section fires

Figure 6 shows the flame and smoke propagation patterns under different working conditions when the fire is located on the branch section. When the wind speed is 0.43 m/s, the smoke rises and impacts the top, and then spreads upstream and downstream of the fire source, forming a phenomenon of smoke backflow; When the wind speed is 0.72 m/s, the smoke generated by the fire source mainly spreads downstream of the fire source, and a small part of the smoke still shows backflow; When the wind speed further increases to 0.87 m/s, there is no significant backflow of smoke and the smoke concentration decreases significantly. The performance under this condition is similar to the phenomenon when the fire source is located in the main tunnel. As the longitudinal wind speed increases, the inertial force of longitudinal ventilation gradually plays a dominant role in the competition with thermal buoyancy, and the phenomenon of smoke backflow gradually decreases.

Figure 6. *The spread of smoke from a fire in the branch section.*

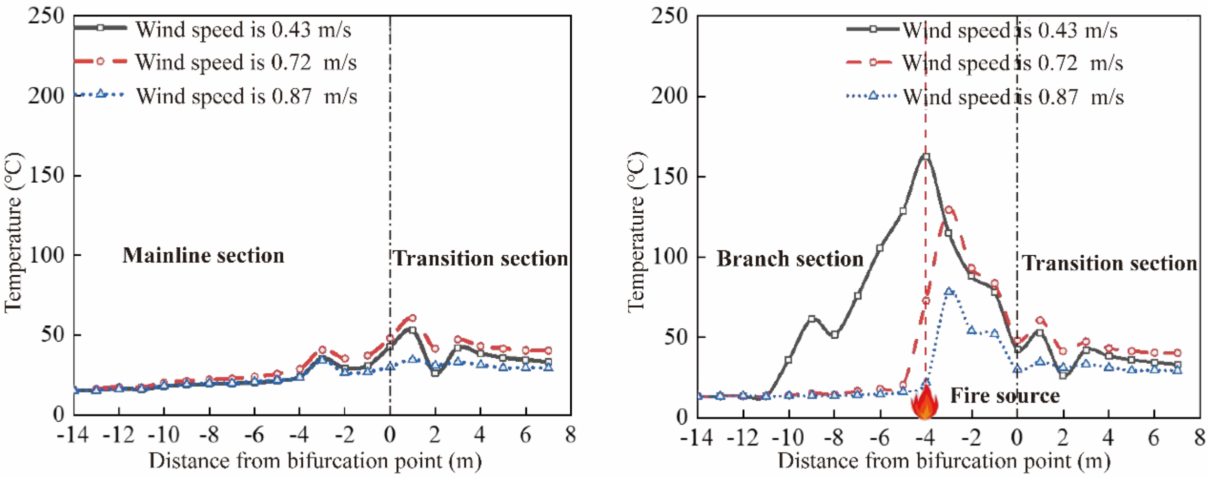

Figure 7. *Temperature distribution at the top of the tunnel under the fire in the branch section.*

Figure 7 shows the temperature point lines at the top of the tunnel under different wind speed conditions when the fire source is located on the branch section. Under the influence of different wind speeds, the top temperature reaches its maximum near the bifurcation point. Due to the structural mutation at the bifurcation point, smoke will accumulate at the top of the transition section IV. The wind speed inside the main tunnel is low, and the smoke accumulated in the transition section IV gradually flows back into the main section, causing the top temperature to rise. The change in wind speed within the branch section affects the smoke in the transition section IV, indirectly affecting the backflow phenomenon within the branch section. As the wind speed increases, the top temperature near the fire source decreases significantly, and the highest temperature shifts downstream of the fire source. The corresponding highest temperatures at wind speeds of 0.43, 0.72, and 0.87 m/s are 163.0, 129.6, and 78.4 ℃, respectively. When the wind speed is 0.43 m/s, the temperature upstream of the fire source increases significantly, indicating a significant phenomenon of smoke backflow at this time. Due to the curved characteristics of the ramp hindering the backflow of smoke, smoke accumulates 9 meters upstream of the fire source, resulting in a significant increase in temperature. When the wind speed increases to 0.72 m/s, the temperature upstream of the fire source is very low, indicating that only a small portion of the smoke is flowing back. When the wind speed further increases to 0.87 m/s, there is no significant change in the temperature upstream of the fire source, indicating no obvious smoke backflow. After entering the transition section, the flue gas experiences a significant decrease in temperature due to the increased cross-section of the transition section. When the wind speed increases to 0.72 m/s, smoke enters the transition section and accumulates, causing a slight increase in temperature inside the transition section. When the wind speed increases to 0.87 m/s, the smoke enters the transition section faster and is quickly carried away without obvious smoke accumulation, resulting in a decrease in temperature in the transition section.

3.3. Smoke spread characteristics of transition section fires

Figure 8. *The spread of smoke from a fire in the transition section.*

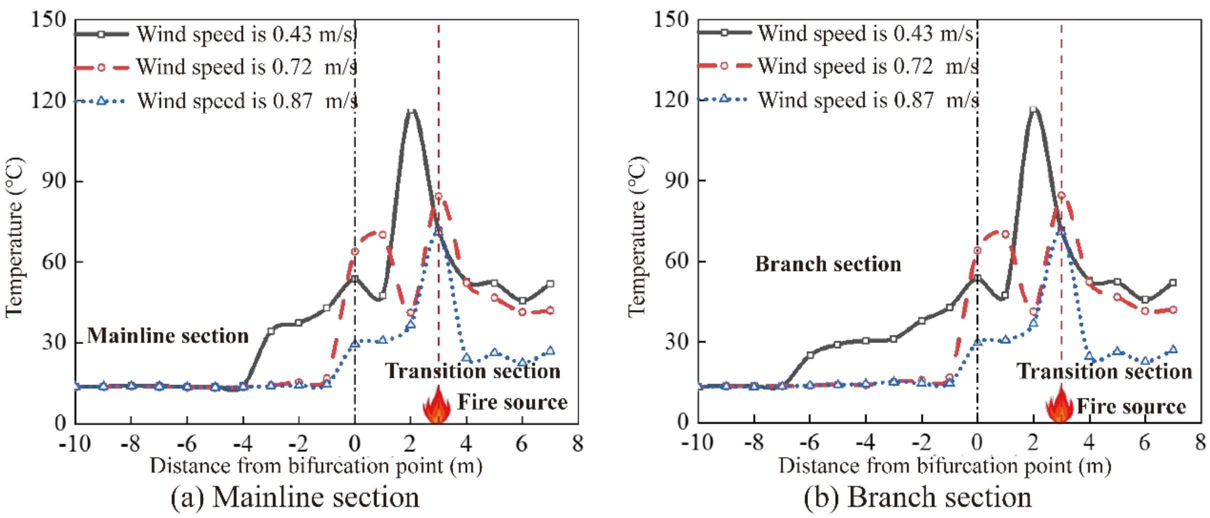

Figure 9. *Temperature distribution at the top of the tunnel under the fire in the transition section.*

Figure 8 shows the flame and smoke propagation patterns under different wind speed conditions when the fire source is located in the transition section, and Figure 9 shows the temperature point line diagram at the top of the tunnel under different wind speed conditions. When the wind speed is 0.43 m/s, the smoke generated by the fire source impacts the top and spreads upstream and downstream of the fire source, resulting in a significant backflow of smoke. When the wind speed is 0.72 m/s, some smoke flows backwards; When the wind speed further increases to 0.87 m/s, the smoke mainly spreads downstream of the fire source. As the wind speed increases, the distribution of smoke in the transition section undergoes significant changes. When the wind speed is 0.43 m/s, the smoke backflow area is not limited to the transition section, and there is smoke backflow in both the main section and the branch section. When the wind speed increases to 0.72 m/s, the reverse flow of smoke is mainly concentrated in the transition section, and the temperature increases significantly at the bifurcation point. When the wind speed is high, it is difficult for smoke to flow back into the mainline and branch sections, and the sudden contraction of the cross-section causes smoke to accumulate in the transition section. After the wind speed further increases to 0.87 m/s, the reverse flow of smoke is concentrated in the transition section, and the temperature is only higher at the fire source. The further increase in wind speed significantly enhances the longitudinal ventilation inertia force, which can quickly discharge smoke, thereby suppressing smoke backflow and reducing smoke accumulation at the top, resulting in a significant decrease in top temperature. Compared with the fire source located in the main section and the branch section, it is more difficult to control the smoke when the fire source is located in the transition section. When the wind speed reaches 0.87 m/s, there is still a small amount of smoke flowing backwards in the transition section. This is because the cross-section of the tunnel transition section suddenly expands, causing the high-speed airflow generated by longitudinal ventilation to mainly concentrate in the lower part of the transition section, with lower longitudinal wind speed at the top. The smoke generated by the fire source cannot be quickly carried downstream and accumulates at the top, resulting in smoke backflow.

4. CONCLUSION

(1) When the fire source is located on the mainline or ramp of the tunnel, increasing the longitudinal wind speed effectively eliminates upstream smoke backflow and reduces peak temperatures, thereby controlling fire scale. This highlights the importance of equipping tunnels with variable-frequency axial fans in practice.

(2) When the fire source is located in the transition section, sudden changes in cross-section cause airflow stratification and the formation of local low-speed zones, resulting in smoke accumulation and backflow. To address this, tunnel designs should incorporate smooth geometric transitions or supplementary ceiling-level jet fans in transition sections to minimize stagnant zones.

(3) Structural mutations at bifurcation points intensify turbulence and promote vortex formation, leading to elevated temperatures at junctions and sidewalls. To mitigate these effects, designers should consider rounded structural transitions, smoke barriers, or targeted extraction vents at bifurcation points to interrupt vortex circulation and facilitate smoke removal.

(4) Increasing wind speed at the entrances of both the main tunnel and ramp is an effective strategy to suppress smoke backflow and limit temperature rise. Operationally, tunnel emergency response plans should prioritize synchronized ventilation control across both the mainline and ramps, with automatic detection systems triggering rapid fan speed adjustments.

Overall, the findings suggest that practical fire safety in arched bifurcation tunnels requires a combination of proactive structural design, such as smoother transitions and strategically placed extraction points, and robust dynamic ventilation control systems capable of adapting airflow distribution in real time.

5. ACKNOWLEDGMENTS

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