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The Influence of Air Curtains on Fire Smoke in Tunnels

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ABSTRACT

To figure out the influence of smoke-proof air curtains on the law of tunnel fire smoke spread, this paper set a simulated fire scene of passenger bus with a fire source power of 25 MW in Fire Dynamics Simulator (FDS), a software for stimulating fire dynamics, to study the law of fire smoke spread in tunnels. At first, this paper analyzed the distribution of smoke temperature, visibility, and CO concentration in each area of the tunnel under the conditions of different jet velocities and angles of the air curtain, and explored the influence of air curtain on the law of fire smoke spread in the tunnel. The research results showed that, when the fire source power was 25MW and the smoke exhaust rate was 100m3/s, in order to effectively control the spread of smoke, the jet velocity of the air curtain should not be less than 7m/s. With the increase of jet velocity, the smoke-proof effect of the air curtain exhibited a trend of increasing first and decreasing later, and the optimal effect was reached at a jet angle of 20°. The influence of jet velocity on the smoke-proof effect was more significant, in case of a fire source power of 25MW and a smoke exhaust rate of 100m^3/s, after comprehensively considering the effect and economy of smoke-proof, it's determined that the best smoke-proof effect could be achieved under the conditions of a jet velocity of 10m/s, and a jet angle of 20°. Our research results proposed reasonable parameters for the smoke-proof of air curtain, which had improved the economy and provided useful guidance for smoke-proof in tunnels.

1. INTRODUCTION

As population is booming in large cities in China, the condition of ground traffic gets worse, to relieve the pressure of ground traffic, vehicular tunnels have been developed fast in recent years [1]. By the end of 2020, 21,316 highway tunnels had been constructed in China, the total length is 21,999.3km, compared with 2019, the increment is 2,249 in number and 3,032.7km in length. Since the space in tunnels has the features of long, narrow, and semi-closed, once a fire occurs, it'll cause great loss to both life and property, in a tunnel fire, the smoke and toxic gases in the fire are the most deadly factors, according to statistics, they account for 85% of the casualties in fire disasters [2, 3]. At present, the ventilation in tunnels in China is mainly vertical ventilation [4], but this ventilation method often interferes with smoke layers and is not conducive to the safe evacuation of downstream personnel. Therefore, this paper aims to study the fire smoke control effect of air curtains in tunnels based on a semi-lateral centralized-type smoke exhaust method, which has important meaning for smoke-proof and personnel evacuation in case of tunnel fire.

Air curtain is a device that can separate two adjacent areas with different climate features by means of high-momentum planar airflows, it is particularly meaningful in situations where traditional physical barriers are not applicable. Recent studies on smoke-proof performance of air curtain have attained fruitful results in terms of experiments and numerical simulations. For instance, Yu et al. [5] carried out small-scale experiment to study the sealing effect of air curtain on fire smoke in tunnel structures, and concluded that the thickness of the air curtain only has a limited effect on smoke-proof, but the installation angle of the air curtain has a great effect on the smoke control. Jung et al. [6] employed a CFD method to study the smoke-proof effect of the air curtain, the method explores the smoke-proof performance of air curtain by changing the jet angle and velocity of air curtain in the tunnel, and the results suggest that a 0° jet angle cannot effectively prevent the spread of the smoke. Gao et al. [7] experimented and simulated the effect of air curtain thickness, jet velocity and angle on smoke confinement under the condition of different fire source power values, and summarized the relationship between fire source power and the design parameters of the air curtain. Wu et al. [8] conducted experiment on the smoke-proof effect of a full-size air curtain in a subway station to explore the influence of jet velocity and angle of the air curtain at different distances from the fire source on the smoke-proof effect, the findings of the experiment revealed that, when the air curtain is closer to the fire source, appropriately increasing the jet angle is conductive to smoke-proof; when the air curtain is relatively far from the fire source, a small jet velocity can completely block the smoke. Tao et al. [9] also used FDS to explore the effects of fire source power, jet velocity and jet angle of the air curtain on the temperature and flow field distribution in the subway tunnel, and their research results showed that, the jet angle of air curtain has a limited influence on the attenuation of vault temperature, when the jet angle is 45°C, the smoke-proof effect of the air curtain is better. Zhang et al. [10] built a full-size high-rise building corridor model in CFD (a software for Computational Fluid Dynamics) to study the effects of air curtain jet velocity, evacuation frequency, wind, fire, and other factors on the efficiency of the air curtain, and the research results showed that the jet velocity of the air curtain is one of the important influencing factor for the performance of the air curtain, and the authors suggested to think about the application purpose and range of the air curtain when setting its parameters. Zhu et al. [11] used FDS to simulate the spread of fire smoke in tunnels with and without air curtain under the condition of a fire source power of 20 MW, and the results proved that setting air curtains on both sides of the fire source can effectively control the fire smoke within the area formed between the two air curtains. Duan and Fu [12] and Hoffman et al. [13] built tunnel models in FDS to study the effect of smoke-proof in tunnels under the combined action of air curtain and mechanical smoke exhaust method, and the results indicated that a 60m or 120m distance between smoke outlet and the air curtain is the best for personnel evacuation, and this smoke-proof method is suitable for long tunnels and single-hole bidirectional tunnels. Smoke is a kind of dust particles, besides smoke-proof, air curtain also has the functions of suppressing smoke dust and improving environment, and it can well help the fire smoke to discharge and suppress the production of dust, other methods could be combined with it based on specific conditions to achieve better control effect [17-20].

Existing studies on air curtain are mainly for subway stations or high-rise buildings [21-23], few of them have concerned about the tunnels. Among the few existing literatures, the main research content is the smoke-proof effect under the sole action of air curtain, very few studies have talked about air curtain under the mechanical smoke exhaust conditions. This paper modeled the tunnel in FDS to study the distribution law of smoke temperature, visibility, and CO concentration in the tunnel under the conditions of different jet velocities and angles and the centralized-type smoke exhaust mode, hoping to provide useful evidences for the design of smoke-proof facilities in case of tunnel fire.

2. SIMULATION AND CALCULATION

2.1 Modeling

At first, a model of a 150m long, 10m wide and 5m high tunnel was constructed in PyroSim, the coordinate origin is the center of the tunnel. According to the NFPA502 standards formulated by American Fire Protection Association [24], the fire source power of the passenger bus is 20MW. In a windy environment, the fire source power will be a bit higher, so in the model, the fire source power (fire source power refers to the heat generated by the fire) was set as 25MW, the fire source size was 6m long, 2m wide and 2m high, and it's located in the center of the tunnel. There're smoke outlets at the top of the tunnel, both the smoke outlets and the air curtains were set along the center line on the tunnel top, and the size of the smoke outlets was 4m×1.5m. According to the requirements of the *Guidelines for Design of Ventilation of Highway Tunnel*, for highway tunnels adopting centralized smoke discharge flue, the vertical distance between two adjacent smoke outlets should not be less than 60m, so in the model, this distance between two smoke outlets was set as 60m, and distance between the air curtain and the smoke outlet was 30m, and the total air exhaust rate of the tunnel was 100m^3/s, the model is shown in Figure 1.

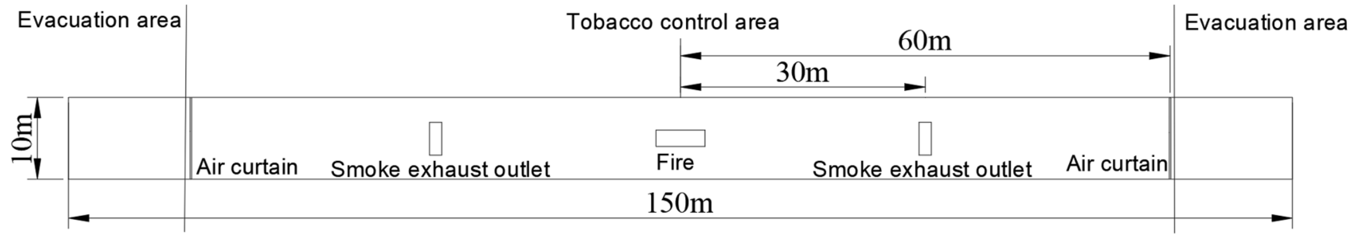


Figure 1. Model of the tunnel

2.2 Calculation conditions

Then, the tunnel fire was simulated in FDS. A part of the software could be used to study smoke control, water sprinkler, and detector activation, and the other part of the software could be used to re-construct the fire scene in civil buildings or industrial buildings. In the simulation, the initial temperature of the tunnel was set to 20°C; the material of inner wall of the tunnel was concrete, and both ends of the tunnel were set as open boundaries; the smoke outlet was set as the boundary condition, the air exhaust rate was 100m^3/s; the air curtain was set as air-supply boundary adjustment. The fire source adopted the unsteady-state t^2 ultra-fast fire, the fuel of the fire source was heptane. According to Wang et al. [18], the width of a single nozzle of the air curtain was set as 0.2m.

2.3 Grids in computational domain

After lots of experiments and simulations, the research of domestic and foreign scholars found that, generally, the ratio of the fire characteristic diameter (D*) to the size of calculation grids (δ_x) takes a value between 4 and 16, then the calculation formula of the characteristic diameter of the fire source is:

$$D^* = \left(\frac{Q}{\rho_0 c_P T_0 \sqrt{g}}\right)^{\frac{2}{5}} \tag{1}$$

where,

Q is the heat release rate of the fire source, kW;

g is the acceleration of gravity, m/s^2;

C_p is the specific heat capacity at constant pressure, J/(kg·K);

T_0 is the ambient temperature, K;

P_0 is the environmental density, kg/m³.

Before numerical simulation and calculation, the independence of the grids was verified and analyzed, to determine a proper size for the grids, four sizes of 0.2m, 0.3m, 0.4m and 0.5m were simulated to observe the changes in the ceiling temperature with time under different grid sizes, and the temperature changes are shown in Figure 2. As can be seen from the figure, with the increase of the grid size, the temperature range decreased. Considering the calculation accuracy and the performance of the computer, the size of grids within 2m from the air curtain was set as 0.2m, and the size of other grids was set as 0.4m, the simulation time was 480s.

2.4 Scheme design and simulation conditions

Jet velocity and jet angle are important factors that can affect the smoke-proof effect of the air curtain. Before the simulation, 5~25m/s was selected as the range of jet velocity and 0°~60°was selected as the range of jet angle for analysis, and the designed work conditions are shown in Table 1. According to the *Guidelines for Design of Ventilation of Highway Tunnel*, in this paper, a smoke temperature lower than 60℃ at 2m height, the human eye characteristic height, and a visibility shorter than 10m, were chosen as the standards of safe personnel evacuation.

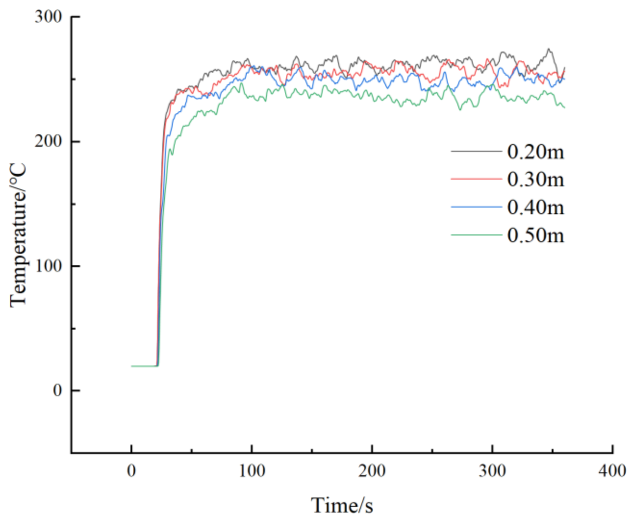


Figure 2. Distribution of ceiling temperature under different grid sizes

Table 1. Work condition settings of the air curtain

Condition	Jet angle (°)	jet velocity ($m \cdot s^{-1}$)
1	0	0
2	0	5
3	0	6
4	0	7
5	0	8
6	0	9
7	0	10
8	0	15
9	0	20
10	0	25
11	10	10
12	20	10
13	30	10
14	45	10
15	60	10

3. THE SMOKE-PROOF EFFECT OF JET VELOCITY

3.1 Analysis of smoke spread

Figure 3 shows the smoke spread situations under the conditions of different jet velocities of the air curtain. In the early stage of the fire, the smoke rose to the ceiling and formed ceiling jets, and then spread to both ends and showed a decline trend. In case that there’s no air curtain in the tunnel, the smoke rose rapidly and spread to both sides, the smoke outlets slowed down the spread, after about 5 minutes, the fire smoke had fully filled in the entire tunnel section. In case that air curtain had been turned on in the tunnel, the air curtain generated a vertical downward wind speed, before the fire source power reached the maximum, the fire smoke had been mainly controlled within the smoke-proof areas formed by the air curtains on both sides. Basically, air curtains of different jets could block the smoke from spreading to both sides, then, with the accumulation of time, the heat release rate of the fire source reached the maximum value. When the jet velocity was 5m/s, the smoke began to break through the air curtain and continued to spread to both sides, indicating that at this time, the air curtain could not effectively block the smoke. When the jet velocity was 8m/s, the smoke would be always controlled within the smoke-proof area. Therefore, only when the jet velocity of the air curtain is greater than 7m/s, can the spread of the smoke generated by a fire source with a power of 25MW be controlled effectively.

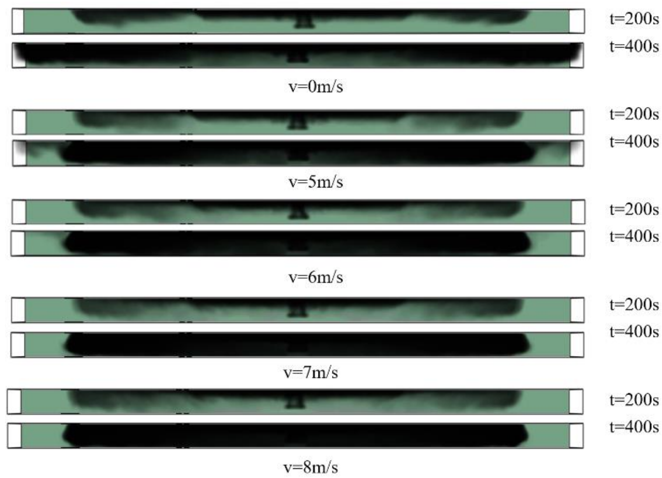


Figure 3. Smoke spread at different jet velocities

3.2 Smoke temperature

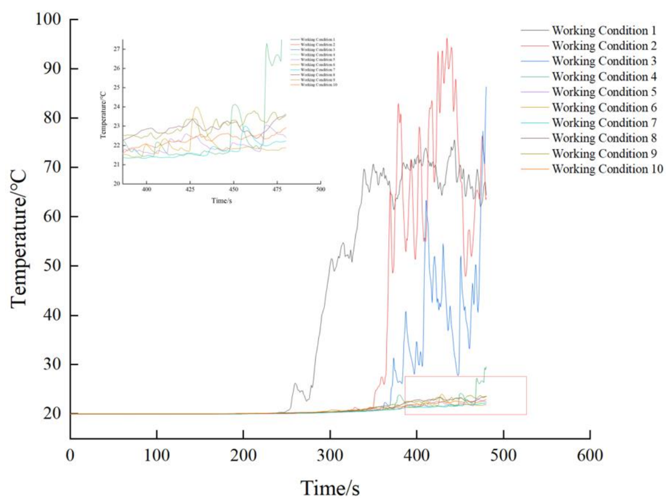


Figure 4. Temperature distribution at a height of 2m

Figure 4 shows the temperature distribution at a height of 2m in the escape area under work conditions 1- 9 and an ambient temperature of 20°C. According to the figure, before the fire source power reached the maximum, the fire smoke had been controlled within the smoke-proof area, and the temperature in the escape area didn't change much, indicating that the air curtain can well block the fire smoke. With the accumulation of time, the heat release rate of the fire source reached the maximum. When the jet velocity was less than 7m/s, the smoke broke through the air curtain and spread to the escape area, and the temperature in the escape area gradually rose with the passing of time, at this time, the maximum temperature at 2m height exceeded 60°C, threatening the safety of human body and indicating that the air curtain could not effectively block the smoke. When the jet velocity was not less than 8m/s, the temperature rise at 2m height was not less than 5°C, indicating that at this time, the smoke had been mostly blocked within the smoke-proof area by the air curtains. Therefore, for fire source with a power less than 25MW, the jet velocity should not be set less than 7m/s. With the changes of the jet velocity of air curtain, the temperature in the escape area showed a V-shaped trend. Therefore, the jet velocity should be set appropriately according to different situations to achieve the best smoke-proof effect. At the height of human eyes in the tunnel, a jet velocity between 9m/s and 15m/s has the best effect in controlling the smoke temperature.

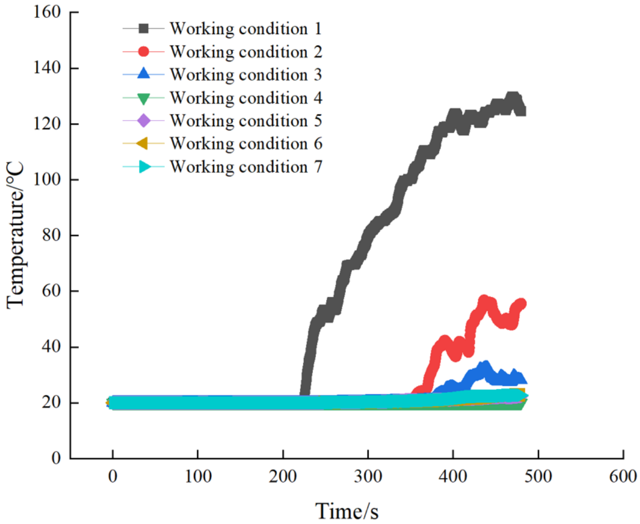
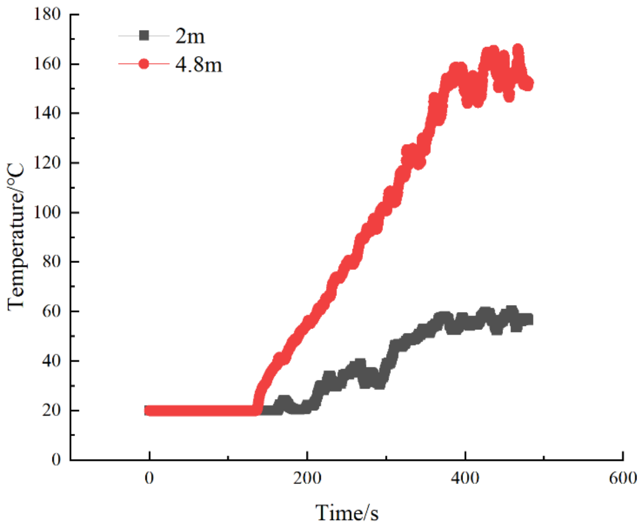
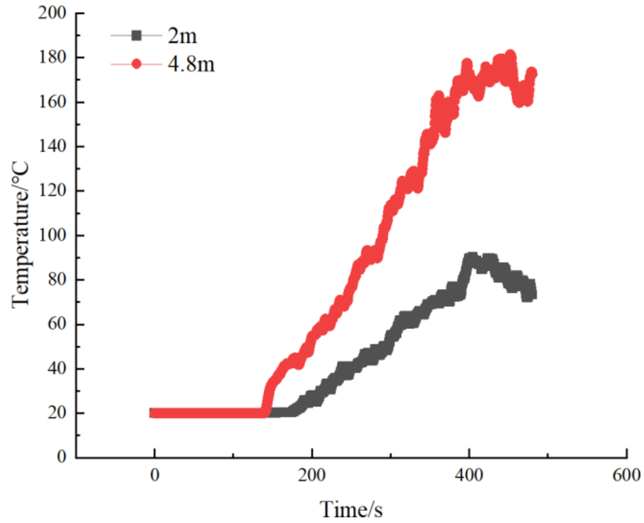


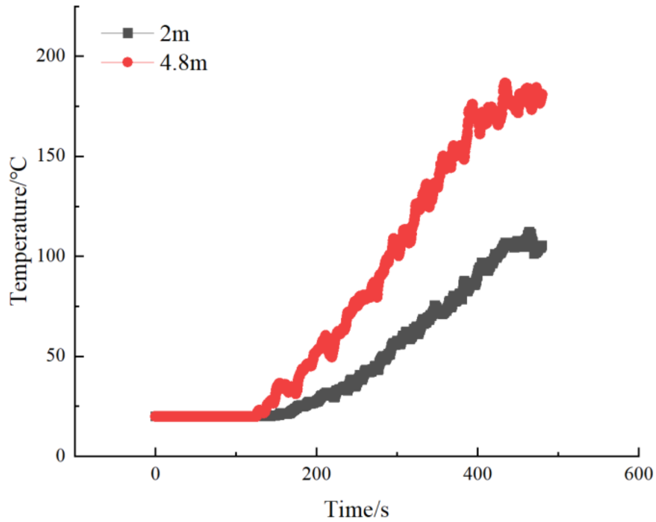
Figure 5. Temperature distribution at the ceiling of the tunnel



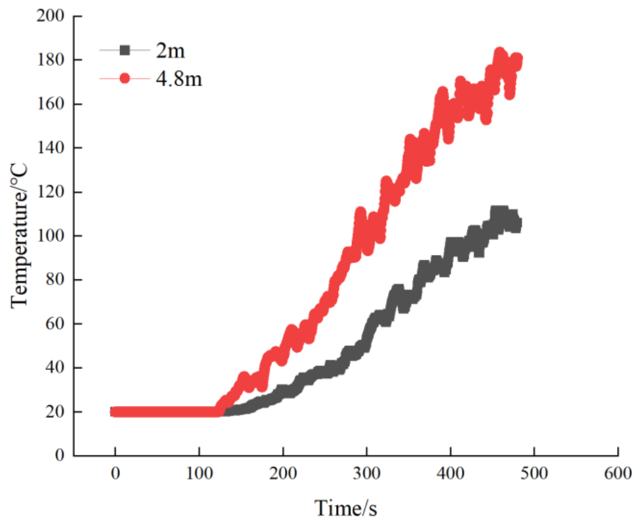
Work condition 1



Work condition 2



Work condition 5



Work condition 7

Figure 6. Temperature distribution at different heights

Figure 5 shows the temperature distribution of the measuring points at the ceiling of the escape area under work conditions 1-7. By comparing these work conditions, it's found that when a fire occurs in the tunnel, the escape area is area that is far from the fire source, at the early stage, the fire source power was relatively small, the temperature in the escape area was close to the initial temperature, then with the passing of time, in case that there's no air curtain, the temperature in the escape area rose gradually, and was between 120°C and 140°C. In case that the air curtains had been installed, smoke had been mostly controlled within the escape area, when the jet velocity was between 5m/s and 8m/s, the temperature in the escape area was less than 60°C; when the jet velocity was higher than 8m/s, the temperature in the escape area was basically the initial temperature. Figure 6 shows the temperature distribution of measuring points at the height of human eyes and at the ceiling in the smoke-proof area under work conditions 1, 2, 5, and 7. According to the figure, the temperature in the smoke-proof area with air curtains was higher than that without air curtain, this is because the air curtains prevented the smoke from spreading to two sides, the smoke could only be discharged from the smoke outlets, so the temperature in the smoke-proof area when there're air curtains in the tunnel was higher that without air curtain.

3.3 Visibility

Figure 7 shows the changes of visibility at a height of 2m under different jet velocities at different distances from the fire source on the right side of the tunnel. As can be seen from the figure, at different jet velocities, the distribution law of visibility in the tunnel at a height of 2m was basically the same. When the jet velocity was greater than 7m/s, the visibility within 60m from the center of the fire source decreased sharply, and was basically shorter than 10m. When the jet velocity was greater than 5m/s, the visibility was about 18m or more, which could meet the evacuation requirements. Then, as the jet velocity was increased continuously, in area 30m farther from the fire source center (the escape area), the visibility was 30m, which was close to the visibility under normal conditions. In the smoke-proof area, with the increase of jet velocity of air curtain, the visibility decreased gradually. This is because the increase of the velocity had destroyed the stratification of the smoke and promoted the mixing of air and smoke, so the visibility had decreased. Thus, setting a suitable jet velocity is conducive to improving the smoke-proof efficiency of the air curtain. From the figure, we can know that when the jet velocity was greater than 10m/s, the changes in the visibility were basically the same, so the visibility was the best at a jet velocity of 10m/s.

3.4 CO concentration

Figure 8 shows the distribution of CO concentration at a height of 2m in the escape area under different jet velocities. In a tunnel fire scene without air curtain, the CO concentration started to rise at about 248s, the value fluctuated continuously, and reached the maximum of 22.8ppm at about 430s. With the increase of the jet velocity of air curtain, the time of CO concentration increase in the escape area was postponed. Under work conditions 2, 3, and 4, the CO concentration started to rise at about 349s, 360s and 372s, respectively; the CO concentration of work condition 2 was 16ppm higher than that of work condition 1, and the CO concentration of work condition 3 was 10ppm higher than that of work condition 1. This is because when jet velocity was less than 7m/s, with the increase of the fire source power, the air curtain could not effectively block the spread of the smoke, and the air curtain aggravated the perturbation of the smoke and the air. When jet velocity was greater than 7m/s, the CO concentration was basically less than 1ppm, indicating that at this same air curtain could effectively control the smoke within the smoke-proof area. When jet velocity was 8m/s, the CO concentration hardly changed from the beginning to the end. Therefore, in order to effectively control the CO concentration, the air curtain jet velocity should not be set less than 7m/s at the height of human eyes.

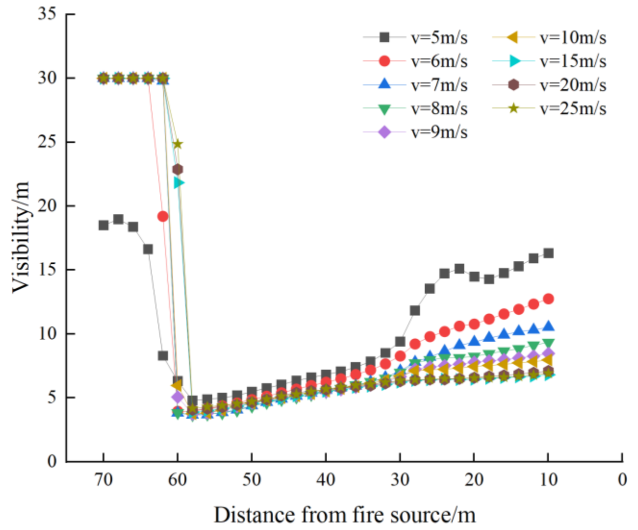


Figure 7. Distribution of visibility at a height of 2m on the right side of the fire source

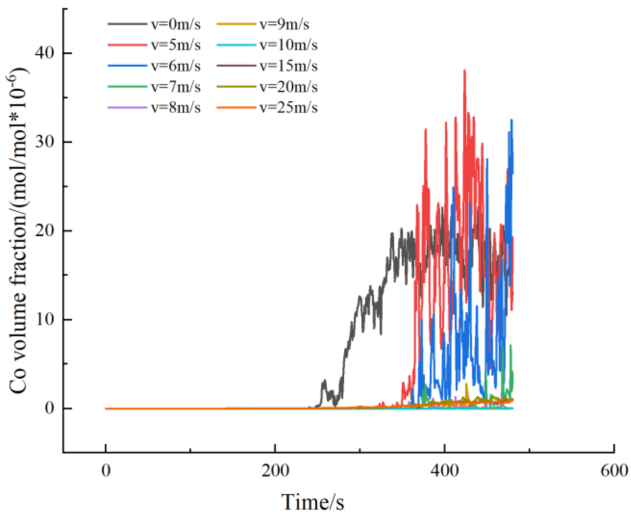


Figure 8. Distribution of CO concentration at 2m height in the escape area

4. THE SMOKE-PROOF EFFECT OF JET ANGLE

In the experiment, the jet velocity of the air curtain was set to 10m/s, the jet angle was changed to observe the changes in smoke distribution, temperature, and visibility at each measuring point at the time moment of 480s. As shown in Figure 9, when a=0° and a=10°, there's almost no smoke leakage, at this time, the air curtain exhibited very good effect in blocking the smoke. When the jet angle was greater than 30°, the smoke began to break through the air curtain and spread to the escape area.

Figure 10 shows the distribution of visibility at different distances and jet angles. According to the figure, when jet velocity was 10m/s, the visibility in the escape area was 30m at different jet angles. At the height of 2m, the trends of visibility curves of different jet angles were basically the same. When jet angle changed within the range of 10°~60°, as the jet angle increased in the smoke-proof area, visibility increased gradually; before reaching the air curtain, visibility had already reached 30m, this is because with the increase of jet angle, the horizontal jet velocity increased, the mixing effect of air and smoke was enhanced, and the visibility had increased.

Figure 9. Smoke spread at different jet angles

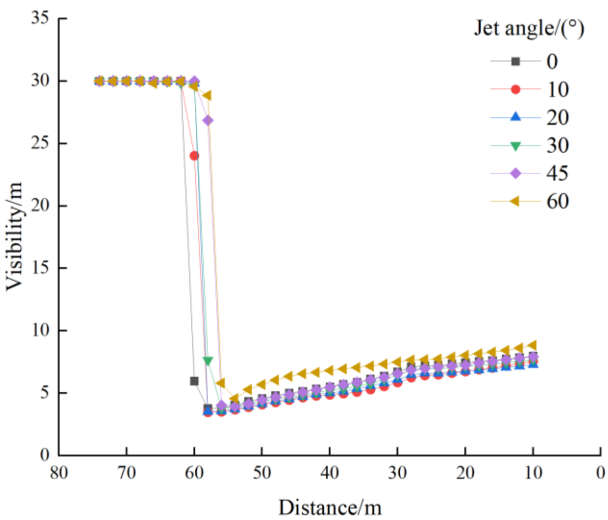


Figure 10. Distribution of visibility at different jet angles

Figure 11 shows the changes of temperature in the escape area under different jet angles. The temperature was always lower than 40°C, and rose gradually with the increase of jet angle, the maximum value was between 22°C and 33°C. When jet angle was greater than 30°, the air curtain could not effectively block the smoke; when jet angle was less than 30°, the trends of temperature changes were basically the same. When jet angle was 0°, 10°, and 20°, most of the smoke had been blocked within the smoke-proof area, at this time, the temperature didn't show obvious increase.

Relevant studies suggested a smoke temperature lower than 60°C at 2m the height of human eyes as the standard for safe personnel evacuation, so in the experiment, this value was taken as the critical temperature value. Figure 12 shows the distribution of the time it takes for the temperature at each measuring point to reach the critical value, the measuring points were located at 2m height and from different distances from the fire source in the smoke-proof area. According to the figure, for the distribution of the time it takes for the temperature at each measuring point to reach the critical value, the law was similar; when jet angle was between 20° and 45°, there're obvious lags in the time to reaching the critical temperature; and the curve of 60° jet angle was the first to reach the critical temperature. Therefore, the jet angle shouldn't be set too large, or it will be not conductive to the personnel evacuation of the smoke-proof area. In summary, when the jet velocity of the air curtain was 10m/s, the recommended value range of the jet angle was 20°~45°, and the smoke-proof effect was the best when the jet angle was 20°.

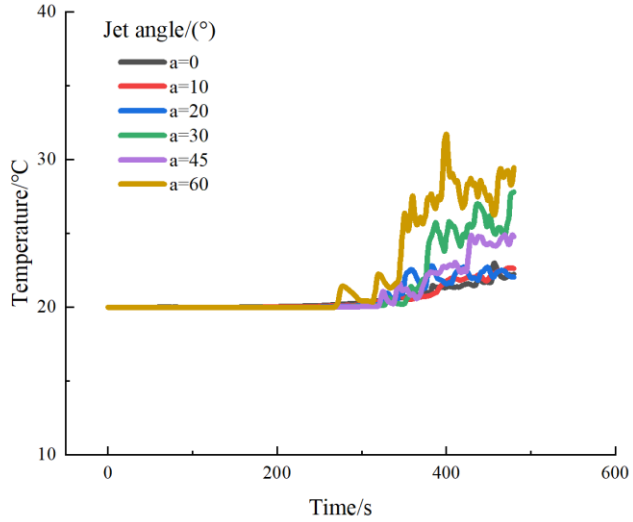


Figure 11. Distribution of temperature in the escape area at different jet angles

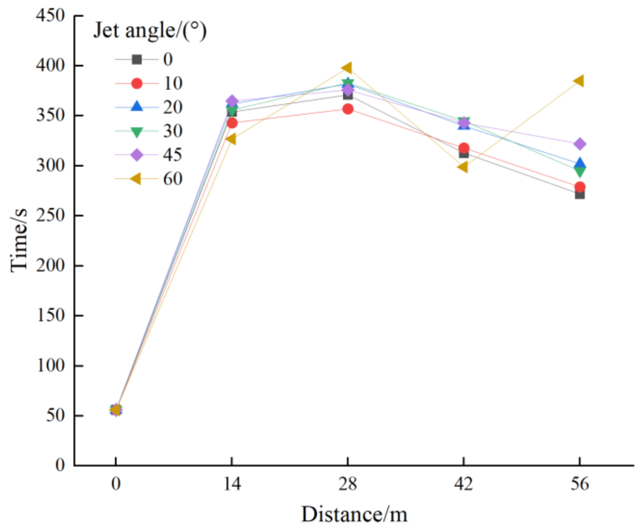


Figure 12. Distribution of the time it takes for the temperature at each measuring point to reach the critical value

5. CONCLUSION

This study performed numerical simulations to study the influence of air curtain on tunnel fire smoke. By setting different parameters, the laws of smoke spread and changes in temperature, visibility and CO concentration were attained. The research conclusions of this paper are:

(1) Compared with fire scene in the tunnel without air curtain, the setting of air curtain had obviously delayed the time it takes for the smoke to spread to the escape area, indicating that the air curtain has a certain effect on blocking the fire smoke, it can prolong the time of safe personnel evacuation, and the influence of jet velocity on the smoke-

proof effect is greater than the influence of jet angle.

(2) Under the conditions of properly-set parameters, the air curtain can effectively control the fire smoke within the smoke-proof area. With the increase of jet velocity, the smoke-proof effect showed a trend of increasing first and decreasing later, and the effect was the best at a jet angle of 20°.

(3) A properly-set jet velocity is conductive to improving the smoke-proof efficiency of the air curtain, at the same time, the jet angle should be increased appropriately.

(4) Through the analysis of the jet velocity and jet angle of the air curtain, it is found that it's not that the larger the air curtain parameters, the better the effect. In case of a fire source power of 25MW and a smoke exhaust rate of $100m^3/s$, when the jet velocity was 10m/s, the smoke-proof effect was the best at a jet angle of 20°.

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