Research on Smoke Flow in Cable Tunnel Fires under the Action of Fine Water Mist and Longitudinal Ventilation

Zhenpeng Bai, Xiaohan Zhao, Qisheng Hu, Hengjie Qin, Haowei Yao

Abstract—**With the rapid urbanization of China, cable tunnels have emerged as prevalent construction projects, and their fire safety has garnered considerable attention. This paper endeavors to investigate the dissemination pattern of fire smoke within cable tunnels and cables, subject to the combined influence of fine water mist and longitudinal ventilation. By constructing an experimental setup, devising experimental protocols, and subsequently collecting and analyzing data, this paper delves into the impact of fine water mist and longitudinal ventilation on the smoke and dust dissemination in utility tunnel cable fires. Furthermore, it elucidates the interaction mechanism between these factors. The results showed that the combined application of water spraying and longitudinal ventilation can effectively limit the spread of fire smoke, substantially decreasing both the temperature and concentration of smoke. Notably, parameters such as wind speed and the direction of longitudinal ventilation play pivotal roles in smoke dissemination. Additionally, this paper utilizes Pyrosim software to model the cable tunnel, examining the influence of fine water mist-related parameters on the fire suppression effectiveness. Overall, this paper offers significant theoretical underpinnings and practical recommendations for enhancing the fire control measures of cable tunnels.**

Index Terms—**Cable tunnel, Water mist, Numerical simulation, Fire**

I. INTRODUCTION

In modern urban construction, utility tunnels are key infrastructure for transporting important resources [1]. However, upon the occurrence of a fire, the cables within cable tunnels are susceptible to generating substantial quantities of toxic and hazardous gases, posing a grave threat to the safety of personnel and the operation of facilities. Consequently, it is of utmost importance to investigate the propagation characteristics of cable fire smoke in utility tunnels and to pursue effective control measures.

Matala et al. [1] conducted numerical simulations to investigate cable tunnel fires, with a particular emphasis on the propagation of fires along power cables and the efficacy of water suppression in preventing cable failures. Sliemon et al. [2] analyzed the impact of cable layer spacing and cable separation on cable compartment fires, deriving a correlation between fire characteristics in cable compartments and cable positioning. Gannouni et al. [3] utilized FDS fire simulation software to model tunnel fires with longitudinal ventilation, employing the Hu model to compare the calculated burnout length post-fire with the simulated FDS values. Their research revealed that the arrival time of a burnout layer is inversely proportional to the heat release rate of the fire and directly proportional to the longitudinal wind speed. Wang et al. [4] investigated the effectiveness of water mist curtains (WMC) in preventing the spread of fire smoke. Wang et al. [5] explored the smoke suppression efficiency and water curtain momentum ratio to characterize the smoke control and insulation effects of tunnel fires.

Blanchard et al. [6] studied the interaction between fine water mist and hot air in longitudinally ventilated tunnels during fires. Liang et al. [7] proposed a new system application using both fine water mist screens and horizontal ventilation systems in tunnel fires. Liu et al. [8] explored the individual and combined effects of a water mist system (WMS) and longitudinal ventilation on the heat release rate (HRR), smoke temperature and degree of post-stratification of tunnel fires. Meng et al. [9] investigated the fire extinguishing performance of a fine water mist fire extinguishing system in a railroad tunnel rescue station. The study considered that the fires were located on the top, inside and underneath the carriages, and the fire sources were gasoline pool fire and stake fire. The design of a fine water mist fire extinguishing system suitable for this fire scenario was proposed and its performance was tested. It collected and analyzed experimental data on temperature, carbon monoxide concentration and radiation flux.

Chen et al. [10] conducted a small-scale experiment to investigate the fire extinguishing effect of fine water mist in tunnels with different longitudinal ventilation rates. Bu et al. [11] investigated the suppression performance of a high pressure fine water mist system in a railroad tunnel rescue

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station by numerical simulation and experiment. It varied the working pressure, droplet diameter and longitudinal ventilation velocity of the fine water mist. Trelles et al. [12] conducted fire extinguishing experiments using a fine water mist system in tunnels. Beard et al. [13] described the modeling of the effect of fine water mist on the spread of major fires in tunnels. The authors have conducted extensive research on fire and ventilation [14-18].

In this paper, a physical model is constructed, and thermocouples, velocity sensors, and CO sensors are strategically placed to gather data. This paper utilizes Pyrosim software to model the cable tunnel, examining the influence of fine water mist-related parameters on the fire suppression effectiveness. Overall, this paper offers significant theoretical underpinnings and practical recommendations for enhancing the fire control measures of cable tunnels.

II. Method

A. Physical Model

For the purpose of this study, a typical cable tunnel was selected as the model, as illustrated in Fig. 1. The dimensions of the tunnel were chosen based on typical values utilized in real-world projects. Specifically, the cable tunnel measures 100 meters in length, 3 meters in width, and 3 meters in height.

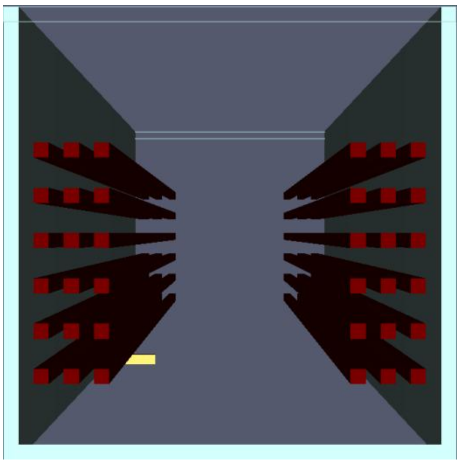

Fig. 1. A physical model of cable in the utility tunnel

B. Boundary conditions

The numerical simulation results are shown in Table 1. The size of the fire source has a length of 0.5 m, a width of 0.5 m and a height of 0.1 m. It is located in the center of the cable tunnel.

The design of a high-pressure water mist extinguishing system hinges critically on the installation of water mist nozzles, which necessitates careful consideration of computational performance and calculation time. It is advisable to avoid an excessive number of fine water mist nozzles, which should primarily be installed in the fire zone. The model in this study was designed using open full water mist fire extinguishing system nozzles with software defaults, with exceptions made for relevant parameters. The fine water mist nozzles were set at a height of 2.7 m, with a spacing of 3 m between adjacent nozzles. Taking the center of the cable tunnel as the reference point, five fine water mist nozzles were installed in the fire zone, each with a flow rate of 15 L/min, a particle size of 400 micrometers, and an atomization cone angle of 120 degrees. The variables under investigation include the horizontal distance between the nozzles and the nozzle flow rate. The layout of the fine water mist nozzles, designated as NOZZLE-NOZZLE4, consists of five fine water mist nozzles in total, positioned at intervals of 3 m.

The smoke propagation patterns were primarily observed using the SmokeViewer tool provided by PyroSim. For temperature detection, thermocouple devices and temperature slices were selected. The thermocouple contamination zones were established horizontally at a height of 3 m below the cable tunnel ceiling, as depicted in the plan view illustrating the placement of thermocouples and CO detectors. The CO detectors, designated as GAS01-GAS04, were positioned 0.2 m below the tunnel ceiling, with the center of the ignition source serving as the reference point. Each CO detector was spaced 3 m apart, totaling 4 detectors. Additionally, the THCP represented a thermocouple referenced to the center of the fire source. Thermocouples were placed horizontally at intervals of 3 meters and vertically at intervals of 0.3 m above the fire source, with a total of 9 thermocouples arranged vertically.

TABLE 1 SIMULATION CONDITIONS OF CABLE TUNNEL WITH FIRE EXTINGUISH.

Case	Fire source Q (MW)	Nozzle spacing D (m)	Spray nozzle flow rate f (L/min)	Ventilation velocity v (m/s)
1	0.5	3	15	0.8
2	0.8	3	15	0.8
3	1.1	3	15	0.8
4	1.4	3	15	0.8
5	1.7	3	15	0.8
6	1.1	1	15	0.8
7	1.1	1.5	15	0.8
8	1.1	2	15	0.8
9	1.1	2.5	15	0.8
10	1.1	3	15	0.8
11	1.1	3	5	0.8
12	1.1	3	10	0.8
13	1.1	3	15	0.8
14	1.1	3	20	0.8
15	1.1	3	25	0.8
16	1.1	3	15	0
17	1.1	3	15	0.4
18	1.1	3	15	0.8
19	1.1	3	15	1.2
20	1.1	3	15	1.6

The main purpose of this paper is to consider factors such as fire power, fire location, fine water mist characteristics and fire power. This paper combined with PyroSim fire simulation software to analyze the diffusion law of smoke under the action of high-pressure fine water mist, the change law of CO gas concentration and the temperature near the location of the fire source when a fire occurs in a cable tunnel, and explained the fire fighting effect of the high-pressure fine water mist system when a fire occurs in a cable tunnel.

III. Results And Discussions

A. Temperature distribution at the top of the cable tunnel

As shown in Fig. 2, it represents the principle governing the impact of the fire source's power on the temperature parameters within the cable tunnel. At a time of 30 seconds, the fine water mist system initiates operation, with the nozzles discharging water mist to suppress the fire. Subsequently, at 60 seconds, a gradual decrease in temperature is observed, indicating that the fire is being progressively controlled. During this period, the maximum temperature drops from 425 ℃ to 250 ℃. Furthermore, it can be deduced that a higher heat release rate (HRR) of the fire source results in higher temperatures, and temperatures at the top of the cable tunnel increase as one approaches the fire source. The temperature decreases gradually as one moves away from the fire source in the vertical direction, and the temperature distribution remains symmetrical on both sides of the tunnel.

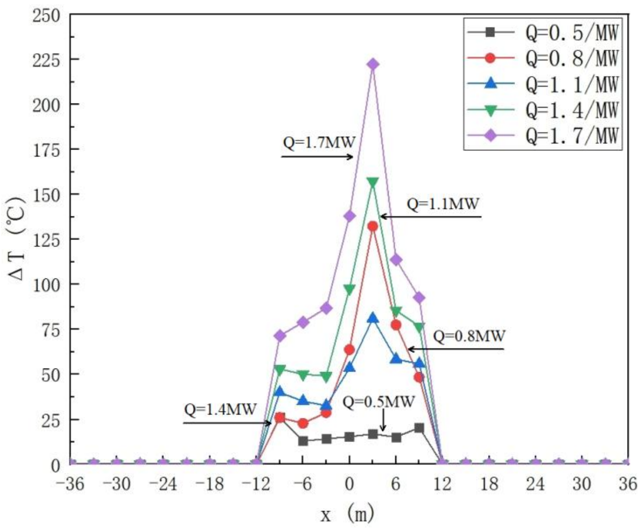

Fig. 2. Temperature distribution at different positions on the top of the cable tunnel at 60 seconds

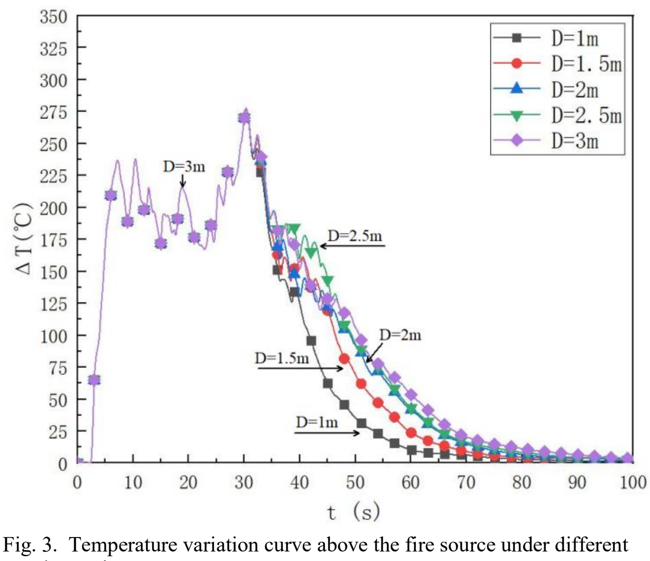

Fig. 3. Temperature variation curve above the fire source under different nozzle spacing

The effect of nozzle spacing on the temperature parameters of the cable tunnel is shown in Fig. 3. As shown in Figs. 3 ~ 5, when a vehicle catches fire within a tunnel, similar temperature variations are observed at other locations along the tunnel. Specifically, as wind speed increases, the rate of temperature decrease at the ceiling of the cable tunnel slows down when fine water mist is applied for firefighting purposes.

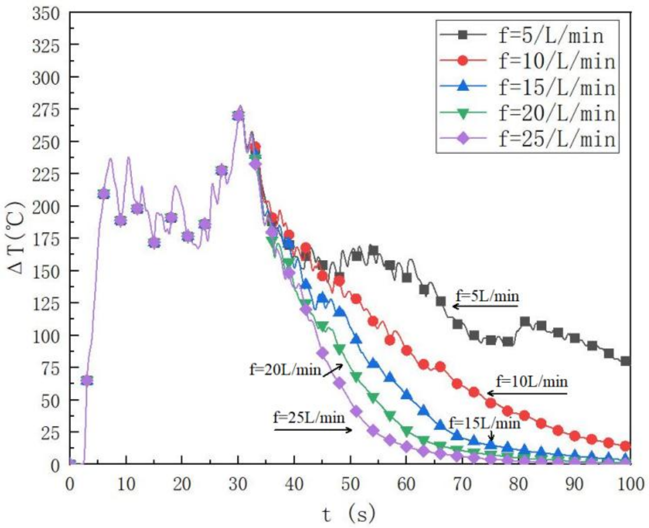

Fig. 4. Temperature variation curve above the fire source under different flow rates

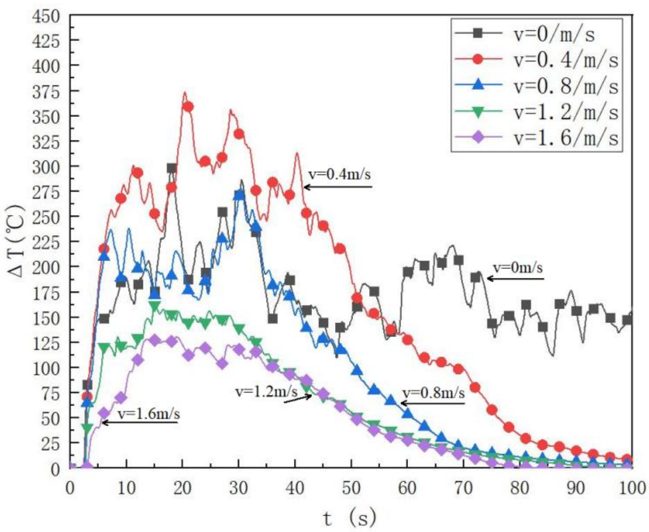

Fig. 5. Temperature variation curve above the fire source under different ventilation rates

B. The variation law of CO gas concentration at the top of the cable tunnel

The variations in CO concentration at the tunnel ceiling directly above the center of the fire source are depicted in Fig.s 6 and 7 for different heat release rates (HRR) of the fire source. Fig. 6 shows the CO concentration changes for fire sources with HRRs of 0.5 MW and 0.8 MW, while Fig. 7 presents the data for HRRs of 1.1 MW, 1.4 MW, and 1.7 MW. Upon the occurrence of a fire, the CO concentration increases. After the application of fine water mist for 15 seconds, the CO concentration rises sharply to a peak value and then gradually decreases. The peak CO concentration reaches approximately 1500 ppm when the fire source's HRR is 0.5 MW, and it increases to 3000 ppm for an HRR of 0.8 MW. As the HRR increases to 1.1 MW, 1.4 MW, and 1.7 MW, the peak CO concentrations reach 3500 ppm, 4200 ppm, and 4800 ppm, respectively. It is evident that the CO concentration increases progressively with the increase in the fire source's HRR. The sudden surge in CO concentration following the activation of the fine water mist is attributed to the suppression of combustion by the water mist, leading to incomplete combustion in the cables and a subsequent rise in CO concentration. As the operating time of the fine water mist increases, the ceiling temperature gradually decreases, resulting in a decline in CO concentration. However, as the fine water mist begins to operate, the rate of reduction in CO concentration gradually slows down. Thus, it can be concluded that the maximum CO concentration increases progressively with the increase in the fire source's HRR.

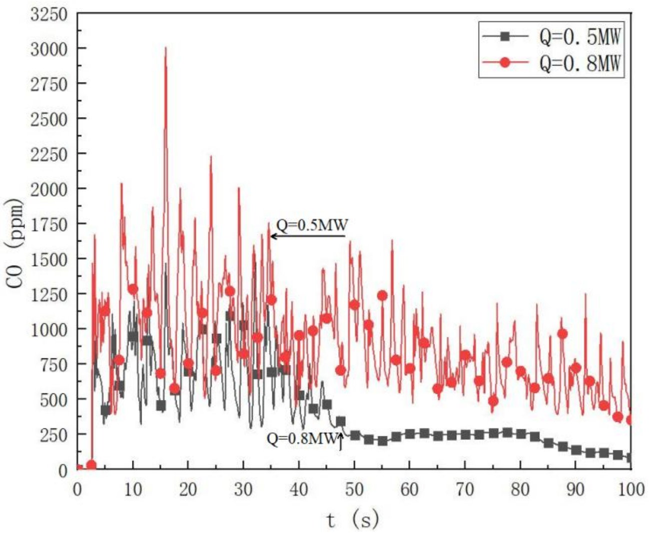

Fig. 6. CO concentration inside cable tunnel with fire source power of 0.5 MW and 0.8 MW

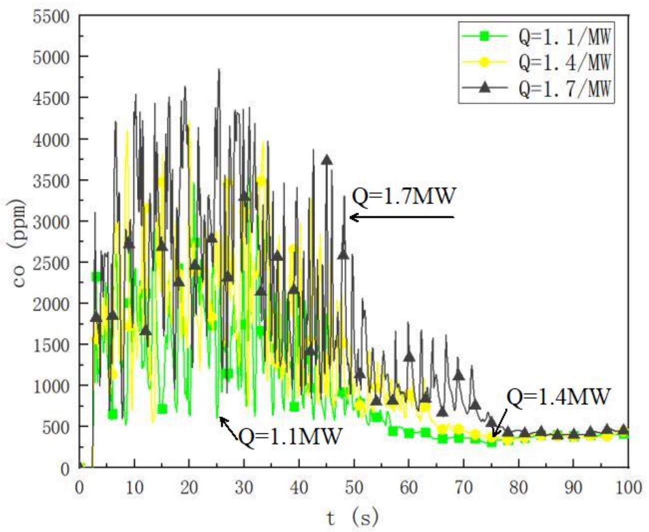

Fig. 7. CO concentration inside cable tunnel with fire source power of 1.1 MW, 1.4 MW and 1.7 MW

As shown in Fig.s 8 ~ 9, the variations in CO concentration beneath the ceiling at the center of the tunnel are presented for different nozzle spacings. Fig. 8 depicts the cases with nozzle spacings of 1 m and 1.5 m. When the nozzle spacing is 1 m, the maximum CO concentration reaches approximately 3000 ppm, whereas for a spacing of 1.5 m, the maximum carbon monoxide concentration is about 3500 ppm. Both concentrations gradually stabilize after 60 seconds. Fig. 9, on the other hand, displays the results for nozzle spacings of 2 m, 2.5 ms, and 3 m. Specifically, for a spacing of 2 m, the maximum concentration is 3250 ppm, stabilizing at 500 ppm after 60 seconds. With a spacing of 2.5 m, the maximum concentration is 3200 ppm, stabilizing at 500 ppm after 65 seconds. Lastly, for a spacing of 3 meters, the maximum concentration is 3600 ppm, stabilizing at 500 ppm after 50 seconds.

Overall, the arrangement of nozzles in fine water mist fire suppression systems may not be optimal when they are spaced too closely together. In fact, small nozzle spacings can actually lead to a poor fire extinguishing effect due to increased mutual interference between nozzles, which reduces fire extinguishing efficiency. Furthermore, overlapping spray areas can affect the uniform distribution of water mist. Additionally, excessively small nozzle spacings can increase installation costs.

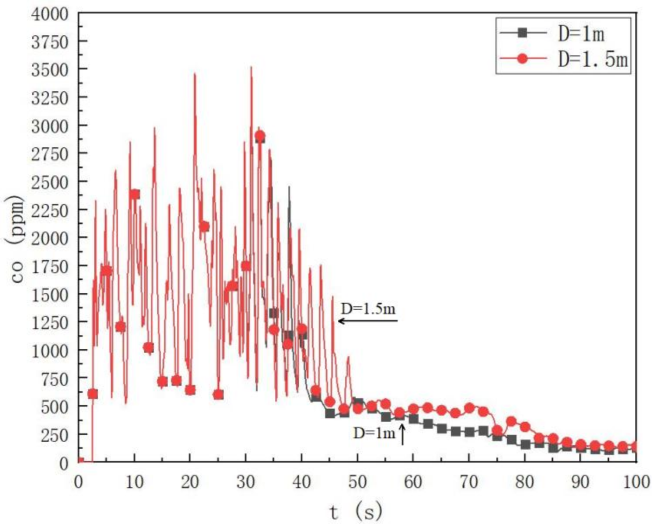

Fig. 8. CO concentration in cable tunnels with nozzle spacing of 1m, and 5 m

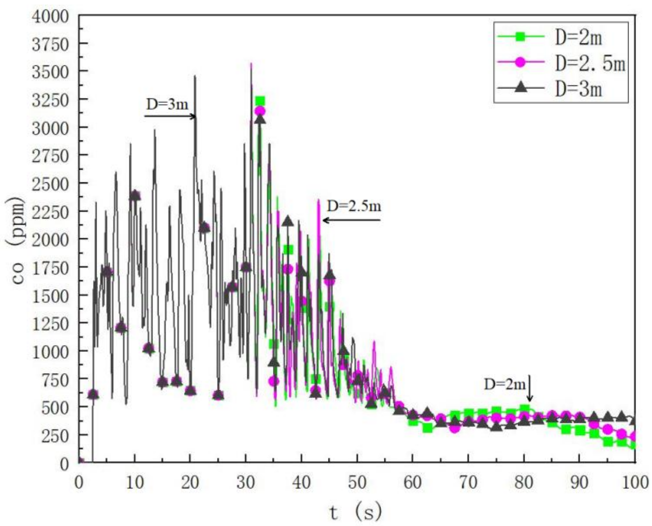

Fig. 9. CO concentration in cable tunnels with nozzle spacing of 2 m, 2.5 m, and 3 m

As can be seen from Fig.s 10 ~ 11, there are corresponding differences in the ability of fine water mist with different flow rates to control the ambient CO concentration. In Fig. 10, the operating conditions before the fine water mist is turned on are consistent. After the fine water mist is turned on, the flow rate of the fine water mist nozzle is 5 L/min, and a large amount of CO is generated during the operation of the nozzle. However, the flow rate of the fine water mist nozzle is too small, and therefore the concentration of CO fluctuates around 1000 ppm, until, at the end, it is not possible to reduce it to a minimum level.

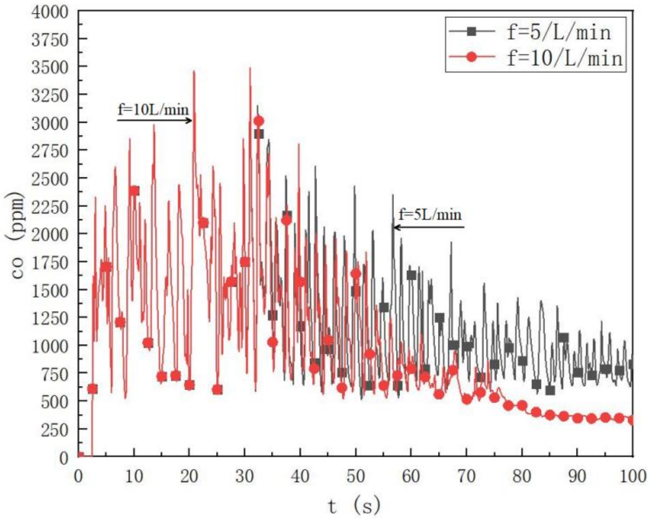

Fig. 10. CO concentration map inside cable tunnel at nozzle flow rates of 5 L/min and 10 L/min

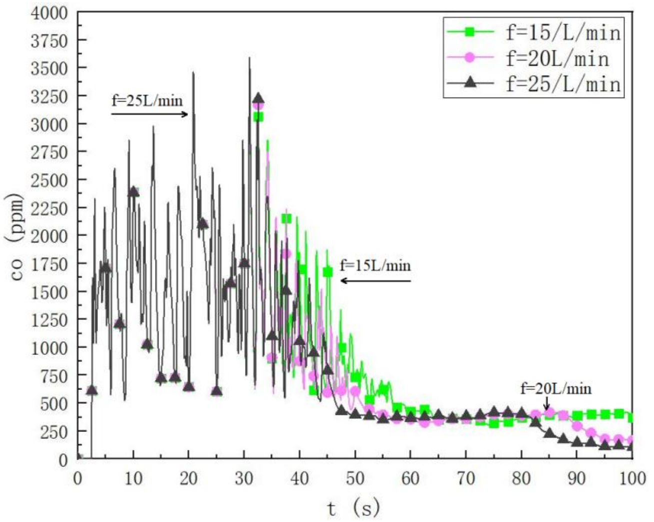

Fig. 11. CO concentration map inside cable tunnel at nozzle flow rates of 15 L/min, 20 L/min, and 25 L/min

In Fig. 11, for fine water mist nozzles with flow rates of 10 L/min, 15 L/min, 20 L/min, and 25 L/min, there is no significant difference in their ability to control the ambient CO concentration. They are all able to control the ambient CO concentration to about 250 ppm in about 50 seconds. In summary, it can be concluded that the higher the nozzle flow rate within a certain range after a fire, the faster the CO concentration decreases and the faster the fire is extinguished. However, considering other factors, the effect of fine water mist fire extinguishing is enhanced as the spray flow rate increases. Although the temperature trends for the four cases with fine water mist nozzle flow rates from 15 L/min to 25 L/min were very similar, there was no significant difference in temperature control at the top of the cable tunnel.

The variation curves of CO concentration at different ventilation rates are shown in Figs. 12 ~ 13. When ventilation velocity is 0 m/s, the CO concentration remains relatively stable in the first five seconds. After 5 seconds, the CO concentration increases sharply and reaches the maximum value of 4000 ppm. Since the wind speed in the duct is 0 m/s at this time, the temperature of the fire source cannot be effectively controlled in a short time, hovering between 250 ppm and 4000 ppm, but never dropping to the lowest point. At this time, the curve fluctuates greatly. When ventilation velocity is 0.4m/s, the fluctuation of the curve is also very stable in the first 5 s. After 5 s, it gradually increases and the CO concentration reaches 2850 ppm. At this time, due to the small ventilation velocity, the temperature of the fire source can be promoted in a short time.

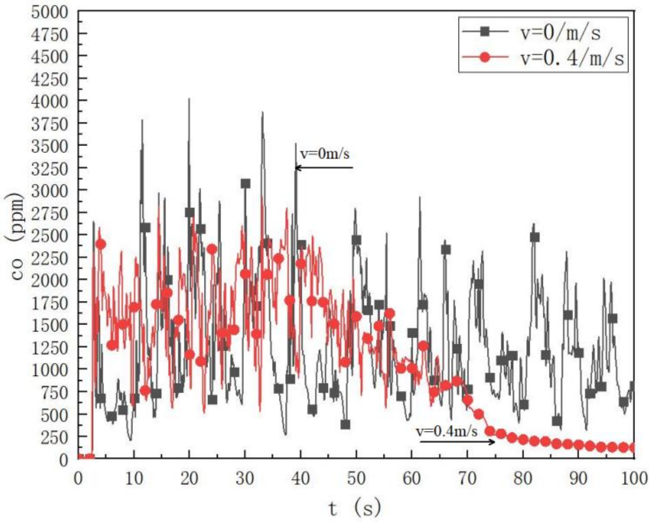

Fig. 12. CO concentration map inside the cable tunnel at ventilation speeds of 0 m/s and 0.4 m/s

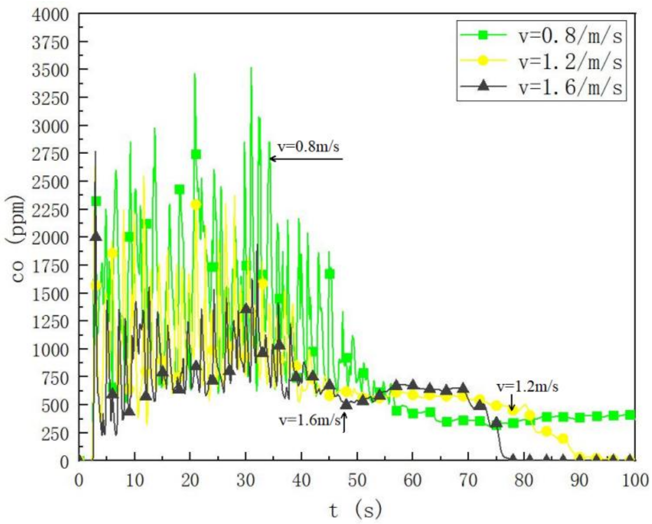

Fig. 13. CO concentration map inside the cable tunnel at ventilation speeds of 0.8 m/s, 1.2 m/s, and 1.6 m/s

As shown in Fig. 13, the curve fluctuation is insignificant when ventilation velocity is 0.8 m/s and 1.2 m/s, both of which are cases where the CO concentration decreases gradually at 50 seconds. In this case, when ventilation velocity is 0.8 m/s, the temperature never drops to 0. When ventilation velocity is 1.2 m/s and 90 s, the CO concentration drops to 0. When ventilation velocity is 1.6 m/s, the maximum concentration of CO reaches 2750 pm. At 40 s, the concentration of CO drops to 500 ppm and fluctuates. At 70 s, the CO concentration suddenly drops and falls to 0 ppm as the fire is completely extinguished and the smoke is completely dissipated by the ventilation velocity.

C. The diffusion law of smoke at the top of the cable

At a fire source intensity of 0.5 MW and a duration of 10 seconds, the fire has just commenced, with smoke gradually disseminating towards the apex of the cable tunnel. Given that the left side of the cable tunnel serves as the air inlet and the right side as the air outlet, the airflow within the tunnel is directed from left to right. When the duration reaches 30 seconds, the fine water mist activation initiates, causing a swift decline in temperature at the ignition source. However, due to the suppression of combustion by the fine water mist, the cables within the duct do not undergo complete combustion, leading to an increase in CO concentration rather than a decrease. By the 60-second mark, the fire source has been fully extinguished as a result of the fine water mist's effectiveness. Subsequently, the smoke starts to disseminate from the top to the bottom of the tunnel. Given that the airflow in the adjacent office area was also directed from left to right, the right side of the cable tunnel becomes completely enveloped in smoke.

As the distance between nozzles increases, the smoke concentration at the apex of the cable tunnel rises, and the lateral distance from the tunnel's center to its sides elongates. Notably, when the distance between nozzles was set at 3 meters, the smoke concentration at the tunnel's top was observed to be 2 meters lower than this spacing. From this, it can be deduced that, to a certain extent, a smaller spacing between nozzle arrangements results in a lower smoke concentration within the tunnel, thereby enhancing visibility and improving the effectiveness of fire suppression.

As the cables undergo combustion, a significant quantity of smoke emerges at the fire scene and rapidly disseminates towards the upper sections, leading to elevated smoke concentrations. Upon activation of the water mist, the smoke layer experiences vertical fluctuations due to the influence of the flow field, with an overall upward trend. As the nozzle flow rate increases, the smoke at the apex of the tunnel becomes less dense, and the concentration of smoke disseminating from the center of the cable tunnel towards its sides diminishes.

When the ventilation velocity is 0 m/s, the smoke disseminates uniformly on both sides of the cable tunnel. As the smoke from the burning fire source accumulates to a certain concentration, it encounters obstruction from the upper cable tunnel and gradually spreads towards the ceiling. Once it has disseminated over a specific area, it becomes more distant from both the fire source and the fine water mist nozzles, leading to a gradual downward dissemination of the smoke and an increase in its thickness. At this stage, the length of the smoke dissemination on both sides is approximately equivalent. As the wind speed increases, the smoke on the inlet side is unable to circulate and instead gradually disseminates towards the exhaust side, causing an augmentation in the thickness of the smoke on the latter side. In summary, in a windless environment, the elimination of smoke is slow. With an increase in wind speed, smoke can be dissipated more rapidly. However, the wind speed should not be too low, as this may exacerbate the ignition source, leading to counterproductive results.

IV. CONCLUSIONS

In this paper, based on the actual cable tunnel fire test, a scaled virtual model was established for simulation analysis using PyroSim software. The conclusions are as follows:

(1) The arrangement of nozzles in the fine water mist fire extinguishing system does not necessarily imply that a closer spacing equates to superior fire extinguishing efficiency. Excessively large spacing can result in an increase in blind spots, thereby diminishing the effectiveness of firefighting. Conversely, while excessively small spacing may reduce blind spots, it can lead to overlapping spray areas, which is neither conducive to enhancing extinguishing efficiency nor cost-effective in terms of installation. Therefore, when designing experiments, it is imperative to comprehensively consider these factors in order to ascertain the optimal nozzle layout.

(2) The system utilizes increased nozzle flow rates to optimize fire extinguishing efficiency to a certain degree. However, it is worth noting that higher flow rates do not necessarily equate to greater effectiveness. In fact, excessive spraying within cable compartments may impede firefighting performance. Additionally, augmented water flow can hinder the upward movement of smoke, causing it to settle, which may result in the accumulation of harmful smoke components on the ground, thereby posing a potential health risk to personnel. Consequently, when adjusting the water spray flow rate, it is crucial to carefully consider the balance between fire-fighting efficiency and personnel safety.

(3) An analysis of the impact of various variables on the distribution of extinguishing times revealed that, among the five factors considered, the flow rate of fine water mist exhibited the most significant contribution to extinguishing efficiency, followed closely by the horizontal spacing of the nozzles. The amount of ventilation and the power of the ignition source also played roles, albeit to a lesser extent. The first two variables are intricately linked to the contact area between the nozzles and the burning material. Given the importance of ensuring standardized installation of automatic sprinkler systems, optimizing the nozzle positions in accordance with the specific layout of the cable room to guarantee that the fine water mist can effectively cover all flammable areas is paramount for enhancing fire extinguishing efficiency.

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