Study on Longitudinal Temperature Decay in Cable Tunnel Near Wall Fire

Zhenpeng Bai, Xiaohan Zhao, Hengjie Qin, Huaitao Song, Haowei Yao

Abstract—**This paper evaluates the influence of natural ventilation on the longitudinal temperature attenuation of cable tunnel wall fires. It took into account the effects of different fuel quantities, cable types, cable layers, and the number of cables per layer. Experimental tests were carried out in a cable tunnel. Results indicated that under natural ventilation the cable burns well. The cable total mass loss rate varies under different conditions. Moreover, under natural ventilation, cable combustion was affected by many factors. This paper analyzed the effect of natural ventilation on longitudinal dimensionless temperature attenuation. A mathematical model was proposed for longitudinal dimensionless temperature attenuation under natural ventilation cases. In addition, a predictive model for maximum temperature rise below the ceiling was proposed to address the effects of heat release rate (HRR) and ventilation on cable tunnel fires. The experimental results were compared with previous research results. Finally, this paper established a calculation equation for dimensionless fire source heat release rate. This paper provides guidance for the fire prevention of cable tunnels.**

Index Terms—**Near wall fire, Cable tunnel, Longitudinal temperature decay, Heat release rate**

I. INTRODUCTION

The fire in cable tunnel is getting serious [1]. It stems from urban construction and the rapid growth of urban population. However, the cable layout in cable tunnels is relatively dense, and the risk of fire in cable tunnels is greater [2]. Wall limitations are important factors affecting the development of flame space, smoke plume air entrainment, and heat transfer. In cable tunnel fires, the location of the combustion source has randomness. The thermal feedback of the generated plume, the degree of restriction of air entrainment by the fire plume, and the flow of smoke after hitting the ceiling and sidewalls are all different due to the different degrees of solid wall boundary limitations of the fire source.

Wang et al. [3] explored the flame propagation and extinguishing of horizontal power cables in utility tunnels. Chen et al. [4] studied the main factors affecting the ventilation effect of cable tunnels. Tang et al. [5] investigated the effects of cable tray spacing on the fire characteristics of mining cables. Yu et al. [6] investigated thermal control and smoke control strategies in a tunnel. Liu et al. [7] studied the maximum ceiling temperature in a tunnel. Tao et al. [8] revealed a correlation study on the prediction of smoke rise time caused by fires in longitudinal ventilation tunnels. Wang et al. [9] studied the effects of cable inclination and longitudinal wind on the flame propagation behavior of cables in utility tunnels. Zhao et al. [10] studied the effect of fire location and air volume on the forced ventilation single end tunnel fires. The author has made extensive research on fire and ventilation [11-15]. Some scholars have studied the diffusion and temperature distribution patterns of flue gas [16-18]. They considered different natural ventilation intensities. The near wall distance at which cable tunnel fires occur is different, and the degree of air entrainment by the fire plume and the flow of smoke after hitting the ceiling and sidewalls are also different. The combustion of cables is only affected by the environment of the cable tunnel and the parameters of the cable itself. Air can freely entrain from around itself, and the thermal radiation generated by combustion is fed back to the outside of itself, partially acting on the surrounding environment.

Previous studies have been conducted on closed cable tunnel fires. However, previous studies have shown that the ignition point of cable tunnel fires is generally located on the longitudinal centerline. The author's earlier research has involved the distribution characteristics of temperature under natural ventilation conditions in cable tunnels. The length of smoke reflux and critical wind speed were studied under mechanical ventilation conditions in cable tunnels. Temperature distribution characteristics under closed conditions of cable tunnel fire were studied. However, there is still a lack of research on the combustion time of cable tunnel fires, such as the longitudinal distribution model of ceiling temperature, and the prediction model of maximum temperature rise under natural ventilation. This paper aims

Manuscript received April 11, 2023; revised June 26, 2024. This work was supported by the Key R&D and Promotion Special Project (Science and Technology Research) in Henan Province (242102240096), Doctor Scientific Research Fund of Zhengzhou University of Light Industry (2021BSJJ048), Henan Province Central Leading Local Science and Technology Development Fund Project (Z20231811020), Zhengzhou University of Light Industry Science and Technology Innovation Team Support Program Project (23XNKJTD0305), Henan Province Key R&D Special Project (231111322200).

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to supplement previous research gaps. This article establishes a physical model of the fire characteristics of cable tunnels and conducts research through model experiments. This paper organized and analyzed experimental data on the combustion time and temperature distribution of cables during the combustion process of cable tunnels, a longitudinal temperature distribution prediction model and a maximum temperature rise prediction model for cable tunnels were established. This article reveals the temperature distribution pattern below the ceiling of cable tunnels. This article provides guiding significance for the structural safety of cable tunnel fires.

II. Method

A. Physical Model

Fig. 1. Physical model of cable tunnel

TABLE 1 CASES OF VENTILATION WITH FIRE IN CABLE TUNNEL

Case	Fuel quantity (ml)	Oil pool (cm × cm)	Cable type	Number of cables per layer
1	10	13×13	ZRYJV	1
2	20	13×13	ZRYJV	2
3	20	13×13	ZRYJV	4
4	10	9.2×9.2	RVVR	1
5	20	9.2×9.2	RVVR	2
6	40	9.2×9.2	RVVR	4
7	10	13×13	RVVR	2
8	40	13×13	RVVR	1
9	10	18.3×18.3	RVVR	4
10	20	18.3×18.3	RVVR	1
11	40	18.3×18.3	RVVR	4
12	10	4×21	ZRYJV	1
13	20	4×21	ZRYJV	4
14	10	4×21	ZRYJV	2
15	10	9.2×9.2	ZRYJV	2
16	10	13×13	ZRYJV	2
17	20	2×42	ZRYJV	2
18	20	4×42	ZRYJV	2
19	20	18.3×18.3	ZRYJV	2
20	20	4×21	RVVR	2
21	20	9.2×9.2	RVVR	2
22	20	2×42	RVVR	2
23	20	13×13	RVVR	2
24	20	4×42	RVVR	2
25	20	18.3×18.3	RVVR	2

The cable tunnel was 6.0 m long, 0.4 m wide and 0.5 m high. As shown in Fig. 1, it is the physical model. As shown in Table 1, it is the experimental tests in cable tunnel fire.

This article conducted 25 cases. The impact of factors such as fuel quantity, pool type, cable type, and number of cables per layer were considered. This article mainly studied the characteristics of longitudinal temperature attenuation, maximum temperature rise, and dimensionless fire source HRR in cable tunnels. Different types of oil pools could vary HRR of the ignition source. The fuel was n-heptane. Cable types were flame retardant bridged polyethylene-clad PVC insulated cables ZRYJV and RVVR. The ventilation method used natural ventilation.

B. Theoretical Analysis

This paper predicted the cable HRR. Heat release rate was obtained during experimental tests could be calculated as follows:

$$15.6\times[\dot{Q}^{*}_{peak}]^{2/5}=\Theta_1+\Theta_2\cdot Fr^{2/3} \tag{1}$$

where, Θ_1 and Θ_2 are parameter. Fr is Froude numbers.

III. Results And Discussions

First, this paper investigated cable combustion time in cable tunnels under the natural ventilation effect. Secondly, this paper studied longitudinal temperature distribution with natural ventilation in cable tunnels. Third, this paper proposed a prediction model of longitudinal temperature distribution of smoke in cable tunnels with the natural ventilation effect. Fourth, this paper proposed a prediction model of ceiling maximum temperature rise in cable tunnels with natural ventilation effect.

A. Combustion of cables in cable tunnel under ventilation

The burning characteristics of cables is displayed in the tunnel, as shown in Table 2.

This article provided the combustion conditions of cables in cable tunnels, the duration of combustion in each case, layer-by-layer cable mass loss, total cable mass loss, and total cable weight loss rate. Under the same conditions, there was no significant difference in the mass loss of each cable layer. However, the total mass loss rate varied significantly under different conditions, indicating that cable combustion in cable tunnels under ventilation conditions was influenced by multiple factors. This article selected several examples to observe what happens when cables burn. It can be seen that in some cases, the cable was completely burned, while in others, it was not severely burned, as shown in cases 2 and 3. Therefore, it is necessary to analyze and study the effects of different factors under natural ventilation conditions on cable tunnel fires.

The total cable mass loss rate in cases 1~3 is 1.3 g/s, 1.57 g/s, and 6.41 g/s. Total cable mass loss rate in cases 4~11 is 1.65 g/s, 1.91 g/s, and 2.23 g/s, 3.61 g/s, 1.01 g/s, 17.18 g/s, 3.10 g/s, and 3.76 g/s. Total cable mass loss rate in cases 14~19 is 0.79 g/s, 1.45 g/s, 3.52 g/s, 0.39 g/s, 0.77 g/s, and 2.45 g/s. The total cable mass loss rate in cases 20~25 is 0.83 g/s, 1.87 g/s, and 1.10 g/s, 3.38 g/s, 1.71 g/s, and 5.80 g/s. Total cable mass loss rate in cases 12~13 is 0.46 g/s and 0.34 g/s.

TABLE 2 NATURAL VENTILATION EFFECT ON CABLE BURNING STATUS NEAR WALL FIRE IN CABLE TUNNEL

Case	Burning time (s)	Quality loss of layer 1 cable (g)	Quality loss of layer 2 cable (g)	Quality loss of layer 3 cable (g)	Quality loss of layer 4 cable (g)
1	80	26.9	25.9	25.4	25.4
2	230	59.9	11.4	108.9	54.9
3	254	225.6	295.6	316.6	291.1
4	128	52.9	52.9	52.4	52.4
5	225	107.4	107.9	106.9	106.9
6	408	218.3	232.8	230.3	228.3
7	117	105.4	105.9	105.4	105.9
8	223	57.9	55.4	55.4	55.4
9	49	210.3	211.3	210.8	209.8
10	69	53.9	53.4	53.4	52.9
11	122	115.4	114.4	115.9	113.4
12	226	26.4	25.9	25.9	25.4
13	1001	81.9	93.4	82.4	77.9
14	265	55.9	51.9	50.9	51.4
15	141	51.9	51.9	50.4	49.9
16	58	52.9	50.9	51.4	48.9
17	529	55.9	51.4	50.4	49.4
18	263	50.9	50.4	48.9	51.4
19	82	50.9	50.4	50.9	48.9
20	523	114.4	108.9	106.4	105.4
21	226	106.4	105.4	104.4	104.4
22	384	106.4	105.4	104.4	104.4
23	137	108.9	109.4	108.9	108.4
24	247	107.9	104.4	104.9	105.4
25	74	108.4	107.4	106.9	106.9

B. Longitudinal temperature distribution of smoke with natural ventilation

To better study longitudinal temperature of the cable tunnel ceiling with the distance from the fire source under different experimental cases, the longitudinal temperature and longitudinal distance length of the cable tunnel ceiling under different natural ventilation cases were studied. The longitudinal dimensionless temperature and distance curves below the ceiling of cable tunnel were obtained.

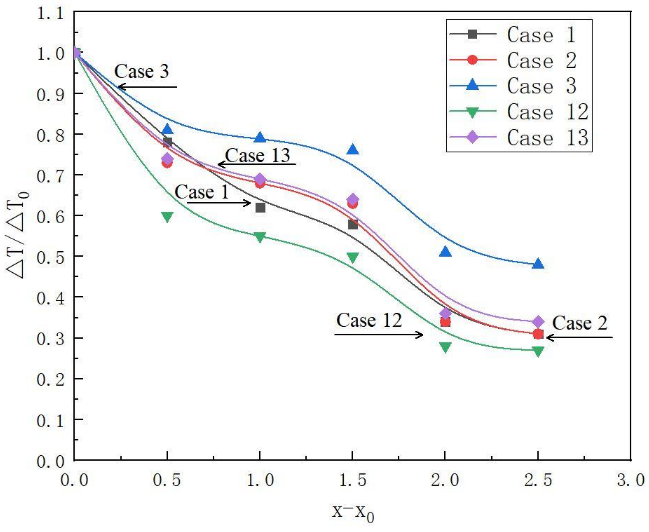

Fig. 2. Influence of natural ventilation in cases 1 ~ 3 and in cases 12 ~ 13 on dimensionless longitudinal temperature distribution in cable tunnel of utility tunnel

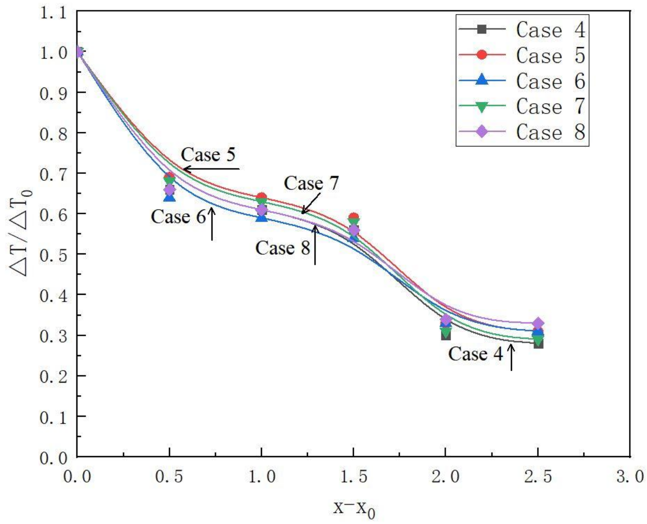

Fig. 3. Influence of natural ventilation in cases 4 ~ 8 on dimensionless longitudinal temperature distribution in cable tunnel

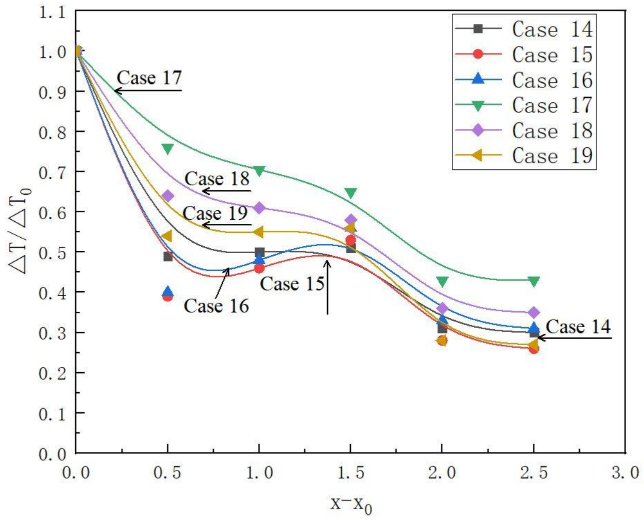

Fig. 4. Influence of natural ventilation in cases 14 ~ 19 on dimensionless longitudinal temperature distribution in cable tunnel of utility tunnel

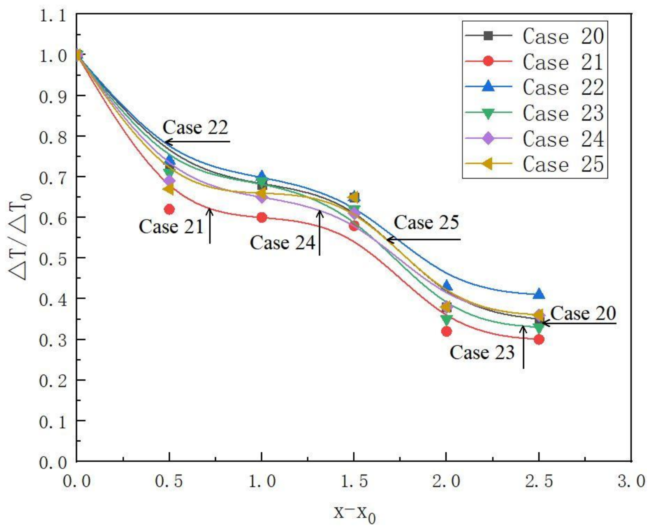

Fig. 5. Influence of natural ventilation in cases 20 ~ 25 on dimensionless longitudinal temperature distribution in cable tunnel

As shown in Figs 2~5, the influence of fire factors on the vertical distribution of horizontal temperature in cable tunnels with natural ventilation could be ignored. The effect of various factors in cable tunnel fire under natural ventilation was analyzed. The dimensionless temperature of the fire source was the maximum. The dimensionless temperature of the cable tunnel decreased with the increase in distance from the fire source. This leads to a gradual decrease in smoke temperature below the ceiling of the cable tunnel. When the position was near the fire source, the temperature decreased rapidly and tended to increase in line with the dimensionless distance. The longitudinal temperature rise distribution in the cable tunnel changes when the cable burns.

As shown in Fig. 6, Equation (2) applies to the dimensionless longitudinal temperature drop under the influence of fire factors with natural ventilation in cable tunnels.

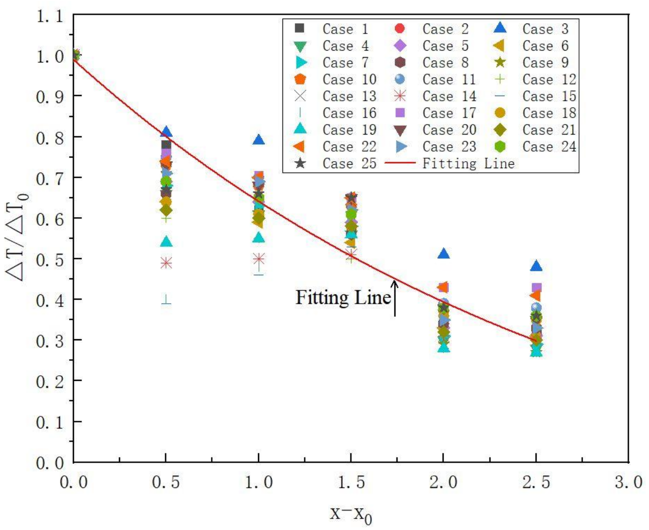

Fig. 6. Formula fitting of dimensionless temperature longitudinal distribution under natural ventilation in the middle of cable tunnel

The smoke temperature rise is ΔT_0 . To obtain the dimensionless temperature rise, it divides the temperature rise at each position measured in the experiment by the temperature rise at the reference point. It uses this value to draw the distance from the reference point $x-x_0$. The exponential power is fitted using the following Equation:

$$\frac{\Delta T_x}{\Delta T_0} = 1.205\, e^{-(x-x_0)/2.934} - 0.216 \tag{2}$$

The fitting results of the smoke temperature rise and attenuation coefficient of the cable tunnel were obtained. According to fitting correlation, the force index fitting method is very close to the experimental data, with an R^2 greater than 0.97. The fitted attenuation coefficient is also very close to the predicted value of the prediction model.

The longitudinal temperature distribution below the ceiling in cable tunnel exhibits an exponential decay distribution, which is consistent with the fitting curve of natural ventilation. This further confirms that there is little correlation between independent temperature and HRR.

C. Prediction model of top maximum temperature rise under natural ventilation

Fig. 7 shows the maximum temperature rise below the ceiling of the cable tunnel under natural ventilation cases. And it compared with the prediction model proposed by Li et al. [19][20]. Results showed that when the cable tunnel catches fire near the wall, the heat generated by the combustion of the cable in the storage pool is not included in the temperature rise below the cable tunnel ceiling. Because the Li's prediction was invalid in a cable tunnel fire. This article proposed a prediction model for the maximum temperature rise of cable tunnel ceilings under natural ventilation fire based on experimental results.

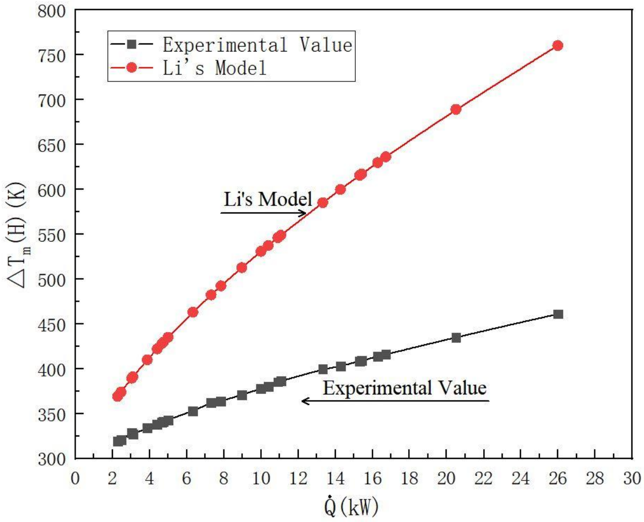

Fig. 7. Influence of natural ventilation on the maximum temperature rise of cable tunnel with HRR and comparison with Li model.

As shown in Fig. 8, under natural ventilation cases, the maximum temperature rise prediction model formula below the ceiling of cable tunnel fits well. Therefore, a prediction model for the maximum temperature rise below the ceiling of a fire cable tunnel near the wall under natural ventilation cases was proposed, as shown in Equation (3).

$$\frac{\Delta T_m(H)}{T_\infty} = 0.674 + 0.593\dot{Q}_H^{*2/3} \cdot H^{-1} \tag{3}$$

where, $\dot{Q}_H^* = \dot{Q}/(\rho_\infty T_\infty c_p \sqrt{g} H^{5/2})$, R^2 is0.99.

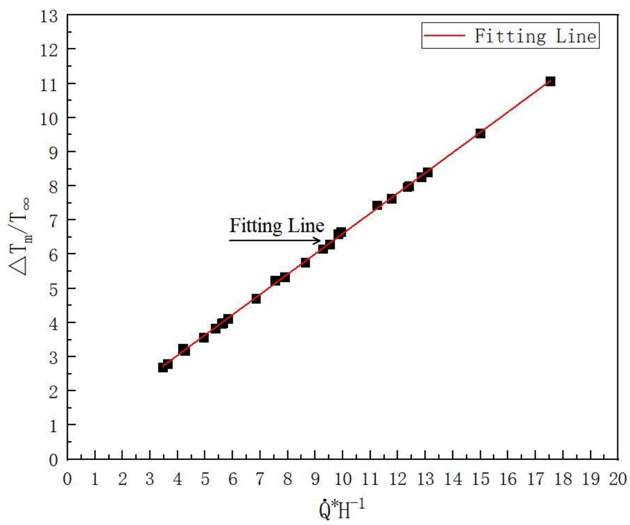

Fig. 8. Formula fitting of maximum temperature rise prediction model of cable tunnel fire under natural ventilation

Equation (3) reflected the positive correlation between the maximum temperature rise in the cable tunnel. In the cable tunnel fire model test near the wall of the cable tunnel, the fire smoke first moved vertically upward and affected the ceiling. Then, a portion of the smoke moved horizontally along the cable tunnel, while another portion diffused along the centerline and entered the cable tunnel vertically.

An experimental study was conducted on the total combustion time of cable tunnel fires. As shown in Table 2, the combustion time of cable tunnel fires can indicate the cable combustion status. ZRYJV cables burned more thoroughly than RVVR cables. While the cable model was ZRYJV, the larger the cable layer, the more complete the combustion.

D. Dimensionless fire source heat release rate

After 65 s, 100 s, and 785 s, the heat release rate in cases 1~3 reached its maximum values of 7.31 kW, 10.90 kW, and 13.32 kW. After 240 s, 115 s, 55 s, 215 s, 220 s, and 30 s, the heat release rate in cases 14~19 reached its maximum values of 2.27 kW, 3.87 kW, 9.99 kW, 2.37 kW, 4.98 kW, and 16.72 kW. As shown in Fig. 9, this paper fits the peak HRR of non-dimensional fire sources in cases 1~3, cases 4~11, cases 14~19, and cases 20~25 with Fr.

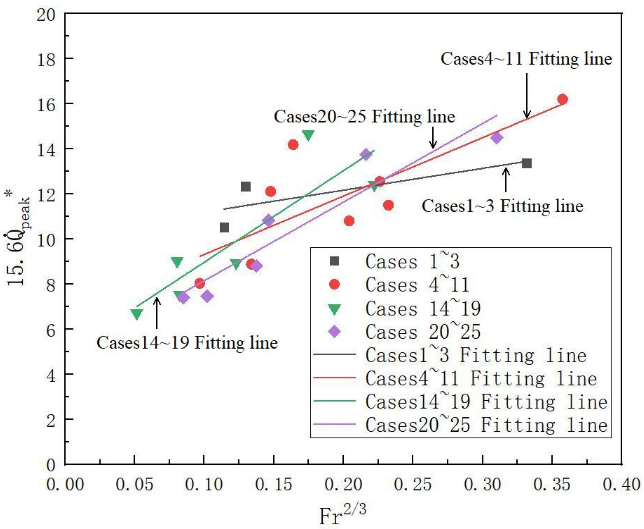

Fig. 9. Formula fitting of heat release rate prediction model of cable tunnel fire under natural ventilation

The non-dimensional heat release rate increases with the increase of Fr. There is difference between in cases 1~3, cases 4~11, cases 14~19, and cases 20~25, which is caused by some assumptions in the model derivation process, especially assuming the equivalent diameter of the oil pool fire and the thickness of the combustible cable. Another possibility is that there may be measurement errors in the process of recording actual fires in the experiment. The fitting equations in cases 1~3, cases 4~11, and cases 14~19 are shown in Equations (4) to (7), respectively, with R^2 values of 0.66, 0.62, 0.75, and 0.88, indicating a good fitting line.

$$15.6\times[\dot{Q}^*_{peak}]^{2/5} = 10.22 + 9.71\cdot Fr^{2/3} \tag{4}$$

$$15.6\times[\dot{Q}^*_{peak}]^{2/5} = 6.72 + 25.92\cdot Fr^{2/3} \tag{5}$$

$$15.6\times[\dot{Q}^*_{peak}]^{2/5} = 4.91 + 40.60\cdot Fr^{2/3} \tag{6}$$

$$15.6\times[\dot{Q}^*_{peak}]^{2/5} = 4.66 + 34.88\cdot Fr^{2/3} \tag{7}$$

Therefore, this paper conducted a series of experimental data analyses on the dimensionless fire source HRR of cable tunnels. It can be concluded that there is a functional relationship between the dimensionless fire source HRR and Fr. It also verified the previous theoretical Equation (1).

IV. Conclusions

This article aims to study the fire characteristics of cable tunnels under natural ventilation cases through experiments. The results indicated that the theoretical equation applied to the longitudinal temperature attenuation of cable tunnels. At the same time, a prediction model was proposed for the maximum temperature rise below the ceiling of near-wall fire cable tunnels with natural ventilation. The main conclusions are as follows:

(1) Various factors such as cable type, cable layout, and cable quantity have a significant impacts on the combustion characteristics of cables in cable tunnels. This affects the quality loss and combustion time of the cables. It further impacts the quality loss rate of cables in cable tunnel fires.

(2) The non-dimensional longitudinal temperature attenuation was influenced by the fuel consumption of the oil pool and cable tunnel, the type and quantity of cables in each layer. This article established a longitudinal dimensionless temperature decay model under natural ventilation conditions.

(3) To study the effects of HRR and natural ventilation on cable tunnel fires, a predictive model for the maximum temperature rise below the ceiling was proposed. Moreover, this article established a relationship between fire source HRR and Fr, which was verified through experiments. This article mainly discusses the fire combustion characteristics of cable tunnels under natural ventilation conditions. It conducted some small-scale cable tunnel fire experiments. However, some initial boundary conditions in this article did not consider the effects of mechanical ventilation and the vertical position of fire sources in cable tunnels. In future work, the influence of mechanical ventilation on the dimensionless power and temperature longitudinal attenuation law of cable tunnel fires should be considered.

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