

Article

Experimental Analysis of Ceiling Temperature Distribution in Sloped Integrated Common Services Tunnels

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Abstract: In this study, a 1/10 reduced-scale model tunnel with one end closed was constructed to investigate maximum temperature profiles beneath the tunnel ceiling during fire events. By varying the heat release rates (HRRs) and tunnel slopes (0%, 2%, 5%, and 6%) and measuring horizontal temperatures longitudinally along the tunnel ceiling, the effects of these parameters were systematically examined. The findings reveal that the distribution of maximum temperatures within a one-end-closed tunnel can be categorized into three distinct regions: far-field, transition, and near-field regions. Notably, milder tunnel slopes correspond to an elevated maximum temperature beneath the ceiling. By employing dimensional analysis, two prediction models were formulated to forecast maximum temperatures beneath the ceiling for fire sources located in the far-field and near-field regions, respectively. These predictive models were validated against experimental data, demonstrating favorable agreement. This study enhances our understanding of the impact of tunnel slope on temperature distribution during fire events in one-end-closed tunnels. Furthermore, the prediction models developed offer practical tools for assessing and mitigating fire risks in such tunnel configurations.



Citation: Li, L.; Wu, G.; Wu, Z.; Huang, H.; Zhang, H.; Gao, Z. Experimental Analysis of Ceiling Temperature Distribution in Sloped Integrated Common Services Tunnels. *Fire* **2024**, *7*, 320. <https://doi.org/10.3390/fire7090320>

Academic Editor: Kaihua Lu

Received: 13 August 2024

Revised: 4 September 2024

Accepted: 10 September 2024

Published: 13 September 2024



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Keywords: common services tunnel; fire detection; slope; ceiling temperature; one-end-closed tunnel

1. Introduction

In recent years, in response to the escalating demands of urbanization and the imperative for sustainable urban development, countries worldwide have increasingly focused on the extensive development and utilization of urban underground spaces. Among these, comprehensive urban underground pipeline tunnels emerge as pivotal assets for fostering city sustainability. However, due to the presence of numerous power and communication cables, as well as natural gas pipelines, urban utility tunnels carry a significant fire risk [1,2]. Urban underground tunnels, with their elongated and confined structures, present significant challenges and safety concerns, especially during fires. Common tunnels are typically divided into different zones, each containing fireproof walls and doors to create isolated environments. These integrated tunnels significantly alter the propagation characteristics and temperature distribution of thermal plumes [3–5]. Unlike traffic tunnels, the presence of fire protection facilities in these tunnels can lead to uneven smoke plume distribution, resulting in substantial smoke accumulation beneath the ceiling, particularly near the closed end. This accumulation causes a noticeable temperature increase near the closed end, which heightens the risk of structural damage to the tunnel and its internal infrastructure [6]. Previous studies have shown that ceiling temperatures during fires in public service tunnels

are higher than those in traffic tunnels [7]. However, in actual projects, comprehensive common services tunnels often feature a certain degree of slope, influenced by factors such as terrain and environmental conditions. The presence of this slope engenders a height differential between the tunnel's two ends, thereby influencing the propagation characteristics of flue gases. Consequently, the temperature distribution beneath the ceiling of graded tunnels deviates from that observed in non-graded tunnels.

Numerous researchers have investigated the temperature distribution patterns during tunnel fires with varying slopes. Ji et al. [8] conducted numerical simulations to explore the influence of tunnel slope on smoke spreading characteristics and longitudinal temperature distribution. Additionally, they proposed a model for longitudinal temperature attenuation upstream of the fire source. Li et al. [9] constructed a reduced-scale model tunnel and analyzed the impact of heat release rate (HRR), longitudinal wind speed, and tunnel geometry on ceiling temperatures. They developed a predictive model for maximum temperature rise beneath the ceiling. Ji [10] examined the effect of ambient pressure on flue gas movement and temperature distribution in inclined tunnels through numerical modeling. Their proposed prediction model accounted for tunnel slope, ambient pressure, and longitudinal wind speed. Yi Liang et al. [11] investigated the influence of longitudinal wind speed and HRR on maximum ceiling temperatures at various slopes using a 1/10 reduced-scale tunnel experiment, validating the theoretical model established by Kurioka et al. [12]. Han et al. [13] analyzed the impact of tunnel slope and port blocking ratio on longitudinal temperature distribution downstream of the fire source through a combination of numerical simulations and experiments. They also proposed a model for longitudinal temperature attenuation downstream of the fire source. Previous research [14] examined the effect of varying the longitudinal position of the fire source on the distribution pattern of maximum ceiling temperatures in a closed-end integrated common services tunnel through theoretical analysis and numerical simulations during fire incidents. They found that the dimensionless maximum temperature rise $\Delta T_{\max}/T_0$ is linearly related to the dimensionless $Q_H^{*2/3}$ in log-log coordinates and established a related prediction model.

Previous studies have primarily focused on examining the distribution of maximum temperatures beneath the ceilings of sloped traffic tunnels during fire incidents. However, most research on temperature distribution in enclosed urban integrated common services tunnels has overlooked the impact of tunnel slope, leading to a divergence from real-world scenarios. Combining insights from prior research on traffic tunnel fires reveals that slope does indeed impact the distribution of maximum temperatures beneath the tunnel ceiling during fire events. In practical terms, due to confined spaces, comprehensive tube tunnels should be equipped with safety features, such as fire doors. When the fire source is closer to the closed end of the tunnel, the maximum temperature distribution beneath the ceiling differs significantly from that observed in typical traffic tunnel fires, owing to heat constraints imposed by the end and side walls.

This study builds on the existing body of research by conducting experimental investigations using a 1/10 reduced-scale model tunnel with one end closed to examine the impact of tunnel slope on the distribution of maximum temperatures beneath the ceiling in integrated common services tunnels. Understanding the distribution pattern of maximum temperatures beneath the ceiling during fires in such tunnels is crucial for effective tunnel design and fire rescue operations.

2. Experimental Setups

The Froude law is applied to build the scale model tunnel [15], and the scaling relationships of some important parameters are shown in Table 1, where s represents entity parameters, m represents model parameters, l is the length (m), and q is the heat flow (kW/m^2).

Table 1. The scaling relationships of some important parameters.

Parameter	Proportional Relationship
HRR (kW)	$Q_s = Q_m (\text{ls/lm})^{5/2}$
Temperature (K)	$T_s = T_m$
Heat flow (kW/m ²)	$q_s = q_m (\text{ls/lm})^{1/2}$

As shown in Figure 1a, the experimental tunnel is scaled at 1:10 (4 m long $\times$ 0.72 m wide $\times$ 0.35 m high) with the left end closed. The test bench's skeleton is constructed using welded steel square bars, while the ceiling, bottom plate, and one side wall are made of 8 mm thick fireproof boards. The other side's wall is made of fireproof glass, allowing for the observation of the test phenomena inside the tunnel. Figure 1b shows the front view of the flame. The slope of the test bench can be adjusted by an electric motor mounted on the stand, with an adjustable range between 0% and 6%. The slope percentage represents the ratio of the height difference between the two ends of the tunnel to the longitudinal span, which is

$$i = \frac{H_1 - H_2}{L} \quad (1)$$

where H_1 is the open end height, H_2 is the closed end height, and L is the tunnel length.

The ceiling temperature is measured using 1 mm diameter K-type thermocouples (T_c). The transverse thermocouples are arranged 20 cm away from the closed end of the model; the interval between two adjacent thermocouples in the longitudinal direction is 10 cm, and the interval is 5 cm in the transverse direction, as shown in Figure 1c.

For the purpose of the following description, the side near the closed end of the tunnel is defined as the upstream of the fire source, and the side near the open end of the tunnel is defined as the downstream of the fire source, as shown in Figure 1d.

The fire source was a propane burner, with the gas flow controlled by a rotating flowmeter to achieve the pre-set HRR. The burner, measuring 20 cm $\times$ 20 cm, was placed against the closed end of the tunnel. The distance from the center of the fire source to the closed end of the tunnel was adjusted by moving the burner along the tunnel's longitudinal centerline (d). According to previous studies [16–18], the HRR of full-size service tunnels typically ranges from 0.2 MW to 1 MW. Therefore, the experiment was conducted with a total of 9 different distances and 5 different HRRs. Based on the Froude scaling law, the HRR for the reduced-scale experiment was set between 1.32 kW and 2.91 kW, equivalent to 0.42 MW to 0.95 MW in an actual urban utility tunnel. The experiments were carried out at slopes of 0%, 2%, 5%, and 6%, with the experimental cases detailed in Table 2.

Table 2. Experimental case setting.

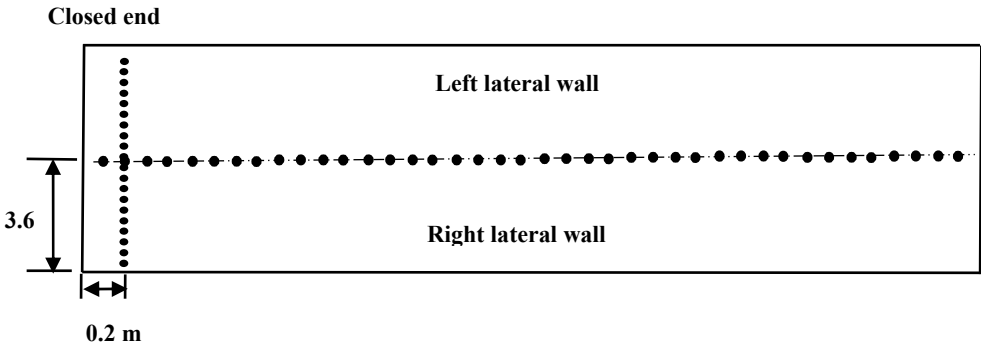
Slope of Integrated Common Services Tunnel i	Heat Release Rates Q (kW)	Distance between the Fire Source and the Closed End d (CM)
0%	1.32	29, 42
	1.59	55, 68
2%	1.99	103, 126
5%	2.38	146, 169
6%	2.91	192



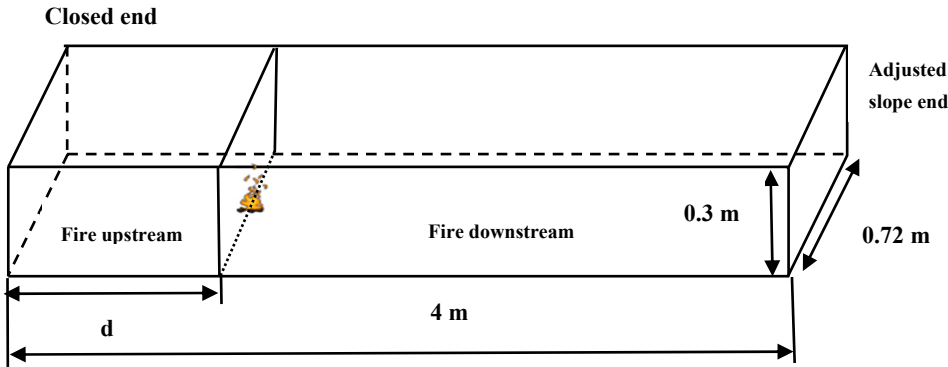
(a) Urban integrated common services tunnel model, 1:10th scale



(b) Flame front view



(c) Thermocouple arrangement



(d) Schematic illustration of model tunnel

Figure 1. Experimental installation.

3. Results and Discussion

3.1. Determination of the Maximum Ceiling Temperature

The longitudinal temperature attenuations beneath the ceiling for various HRRs and tunnel slopes are illustrated in Figure 2. A longitudinal examination of the figure reveals that milder tunnel slopes correspond to elevated longitudinal temperatures beneath the ceiling. Notably, tunnel slope exerts a significant influence on maximum ceiling temperature. Therefore, the incorporation of slope effects is imperative in the development of prediction models for maximum temperature rise in elongated and confined passages [19–24].

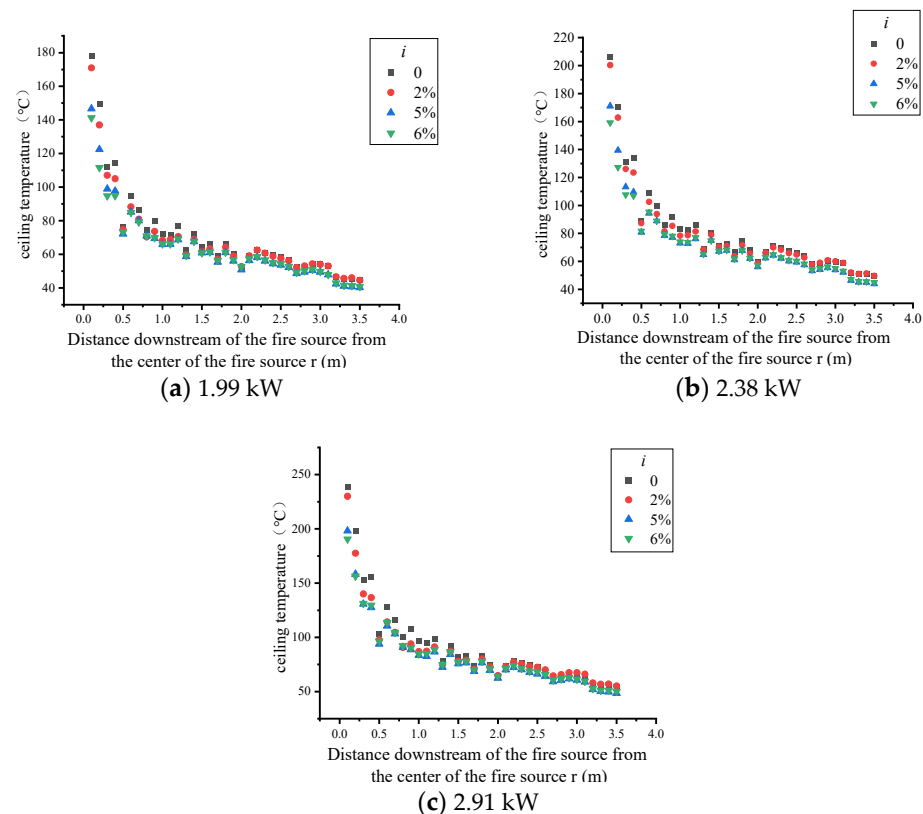


Figure 2. Longitudinal temperature along the ceiling for different HRRs.

Figure 3 shows the distribution of the maximum temperature beneath the ceiling upstream for different tunnel slopes. As shown in Figure 3, it can be seen that when $d \geq 103$ cm, the maximum temperature ($T_{\max}$) beneath the ceiling of the tunnel remains stable as the distance (d) from the center of the fire source to the closed end of the tunnel decreases. This is because, when the fire source is far away from the closed end, the distance between the fire source and the closed end has a rather limited influence on the temperature profile here. In the region where 68 cm $< d < 103$ cm, $T_{\max}$ will gradually decrease as d decreases. This occurs due to the asymmetry of the tunnel at both ends, which can result in uneven smoke accumulation and flame tilt. Consequently, there are differences in smoke temperature and flow on either side of the flame, leading to reduced thermal radiation and a lower ceiling temperature [25,26]. When $d \leq 68$ cm, $T_{\max}$ will gradually increase as d decreases. This is because, as the fire continuously approaches the closed end, more and more hot thermal plume will flow back to the fire source and intensify the influence of anti-buoyancy wall jets [27], which causes a remarkable increase in the ceiling temperature.

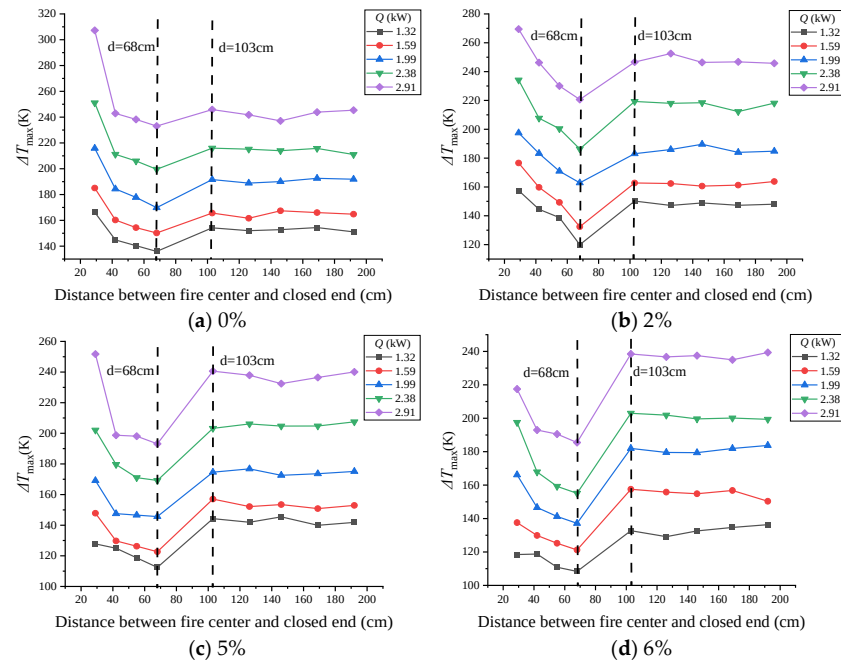


Figure 3. Distribution of maximum temperature beneath the ceiling for different tunnel slopes.

3.2. Correlations for the Maximum Ceiling Excess Temperature

To precisely delineate the region and extent of the closed end's influence, Figure 4 depicts the variation in the dimensionless maximum ceiling excess temperature ($\Delta T_{\max}/T_0$) with the dimensionless distance from the closed end of the tunnel (d/h). As illustrated in Figure 4, the dimensionless maximum ceiling excess temperature ($\Delta T_{\max}/T_0$) undergoes distinct changes in response to the fire's location, enabling its classification into three distinct regions: the near-field region ($d/h \leq 2.27$), the transition region ($2.27 < d/h < 3.43$), and the far-field region ($d/h \geq 3.43$).

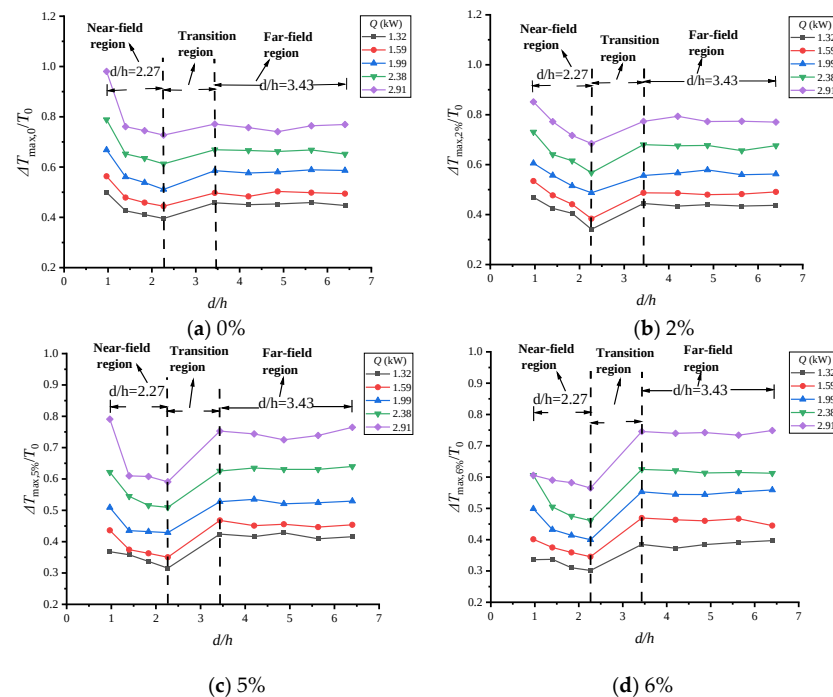


Figure 4. Dimensionless temperature rise vs. dimensionless length.

Based on the definitions of the far-field and near-field regions of the closed-end fire source above, the closed-end effect has limited impact on fires in the far-field region. The dimensionless maximum temperature rise $\Delta T_{\max}/T_0$ is independent of the distance between the fire source and the closed end. It can be fitted with a dimensionless HRR of Q_h^* through previous empirical models [14].

Figure 5 illustrates the dimensionless maximum ceiling excess temperature plotted against $Q_h^{*2/3}$ for fires located in the far-field region of tunnels with slopes of 0%, 2%, 5%, and 6%. As depicted in Figure 5, a linear relationship is observed between $\Delta T_{\max,i}/T_0$ and $Q_h^{*2/3}$ when plotted on log-log coordinates for the specified slopes within the tunnel. The fitted data closely align with the findings reported in previous studies [14]. The expression of the fitting relationship is represented by Equation (2):

$$\frac{\Delta T_{\max,i}}{T_0} = \alpha Q_h^{*2/3}, Q_h^* = \frac{Q}{\rho_0 c_p T_0 \sqrt{g} h^{5/2}} \quad (2)$$

where i is the slope, $\Delta T_{\max,i}$ is the maximum temperature rise located in the far-field region for the tunnel slope i (K), T_0 is the ambient temperature (K), ρ_0 is ambient air density (kg/m^3), c_p is specific heat capacity of the air ($\text{kJ}/(\text{kg}\cdot\text{K})$), h is the height of the tunnel model (m), and g is the gravitational acceleration (m/s^2).

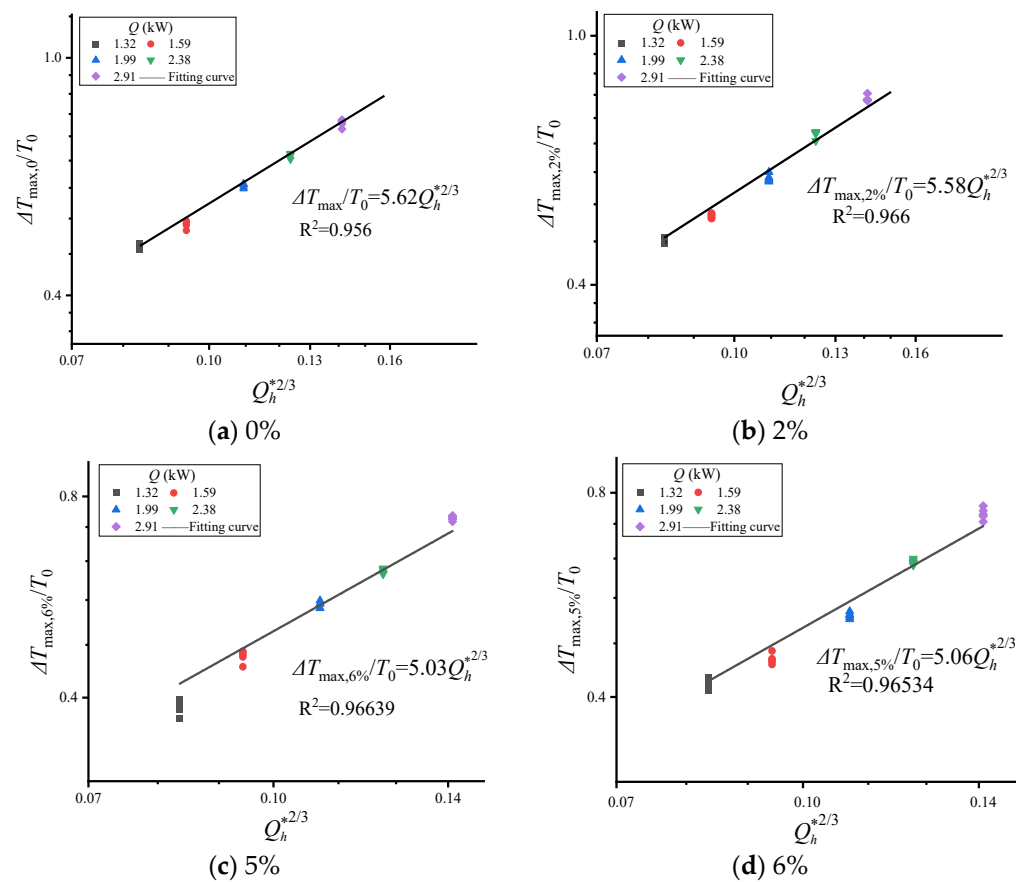


Figure 5. Dimensionless maximum temperature rise in the far-field region of the closed end vs. $Q_h^{*2/3}$.

The relationship between slope i and coefficient α is represented in Figure 6, from which it can be seen that α decreases linearly with increasing slope. The expression for the fitted relationship is

$$\alpha = -11.16i + 5.68 \quad (3)$$

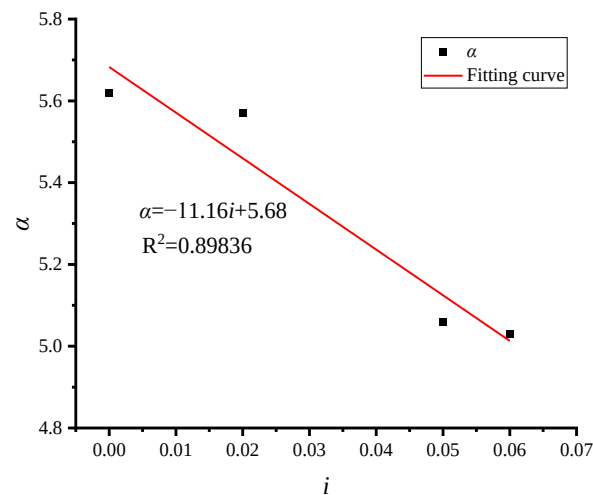


Figure 6. Fitting coefficient α .

Therefore, $\frac{\Delta T_{\max,i}}{T_0}$ can be expressed as Equation (4).

$$\frac{\Delta T_{\max,i}}{T_0} = (-11.16i + 5.68)Q_h^{*2/3} \quad (4)$$

As shown in Equation (4), $\Delta T_{\max,i}/T_0$ exhibits a linear relationship with the tunnel slope. To assess the formula's accuracy, the experimentally measured temperatures are compared with the values calculated using Equation (4), and these results are further compared with the experimental data reported by Li et al. [28]. The error, as depicted in Figure 7, falls within 20%. Hence, Equation (4) can effectively predict the dimensionless maximum temperature rise beneath the ceiling when the fire source is positioned in the far-field region across various integrated common services tunnel slopes.

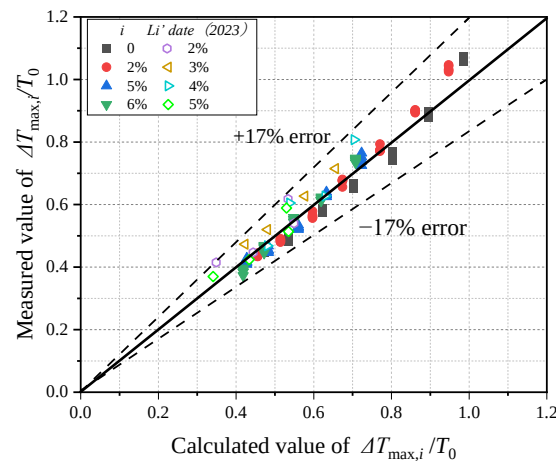


Figure 7. Comparison of calculated values with experimental data.

For fires situated in the near-field region, the proximity of the fire source to the closed end substantially impacts the maximum temperature of the ceiling. Specifically, as the fire source approaches the closed end, the maximum temperature beneath the ceiling increases. Empirical models based on previous research [14] allow for the fitting of the modified dimensionless maximum temperature rise ($\Delta T_{\max,di}/\Delta T_{\max,i}$) with the dimensionless heat release rate (Q_d^*).

Figure 8 illustrates the dimensionless maximum ceiling excess temperature plotted against Q_d^* for fires located in the far-field region of tunnels with slopes of 0%, 2%, 5%, and 6%. As depicted in Figure 8, a linear relationship is observed between $\Delta T_{\max,di}/\Delta T_{\max,i}$

and Q_d^* when plotted on log-log coordinates for the specified slopes within the tunnel. The fitted data closely align with the findings reported in previous work [14]. The expression of the fitting relationship is denoted by Equation (5)

$$\frac{\Delta T_{\max,di}}{\Delta T_{\max,i}} = A Q_d^{*B}, Q_d^* = \frac{Q}{\rho_0 c_p T_0 \sqrt{g} h d^{3/2}} \quad (5)$$

where i is the slope, $\Delta T_{\max,di}$ is the maximum temperature rise located in the near-field region for the tunnel slope i (K), and A and B are constants.

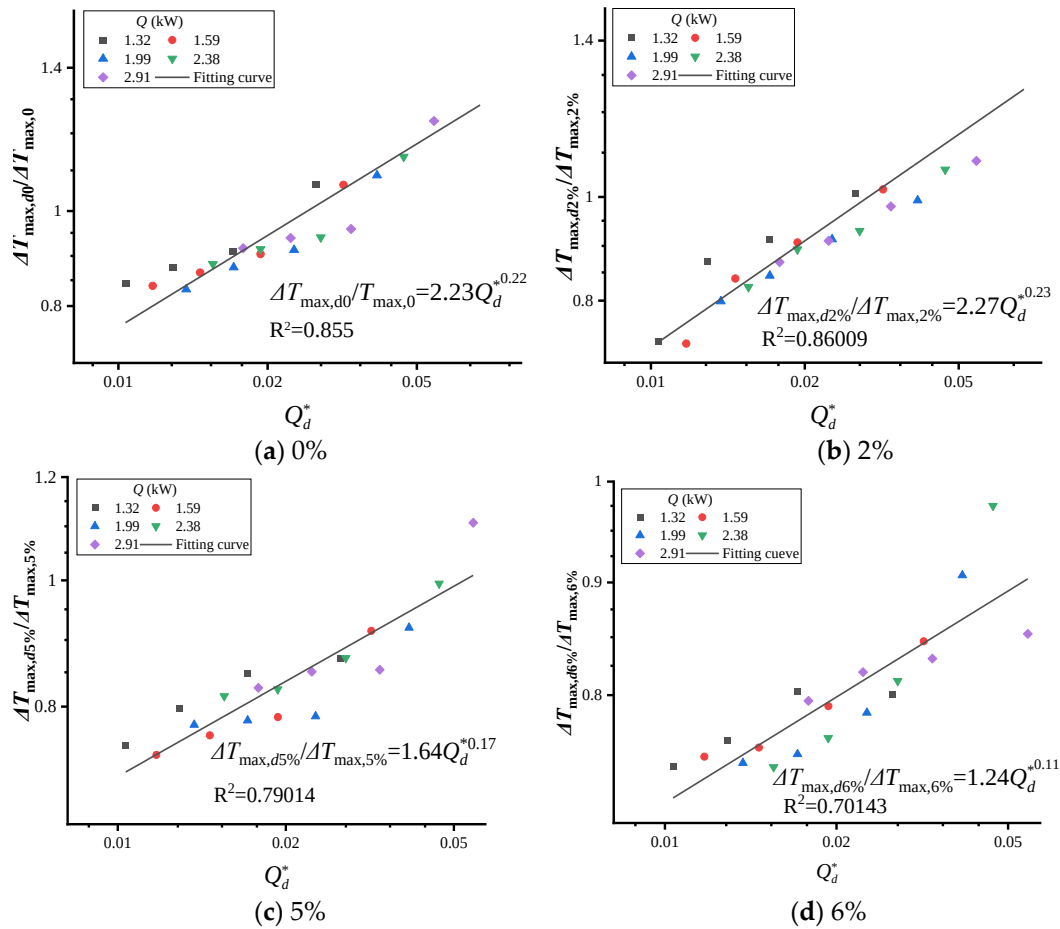


Figure 8. Dimensionless maximum temperature rise in the far-field region of the closed end vs. Q_d^* .

Figure 9 illustrates the relationship between slope i and coefficients A and B . As depicted in Figure 9, coefficients A and B exhibit a linear decrease with increasing slope. Equations (6) and (7) can be tabulated to demonstrate the relationship between coefficients A and B and slope:

$$A = -16.73i + 2.39 \quad (6)$$

$$B = -1.77i + 0.24 \quad (7)$$

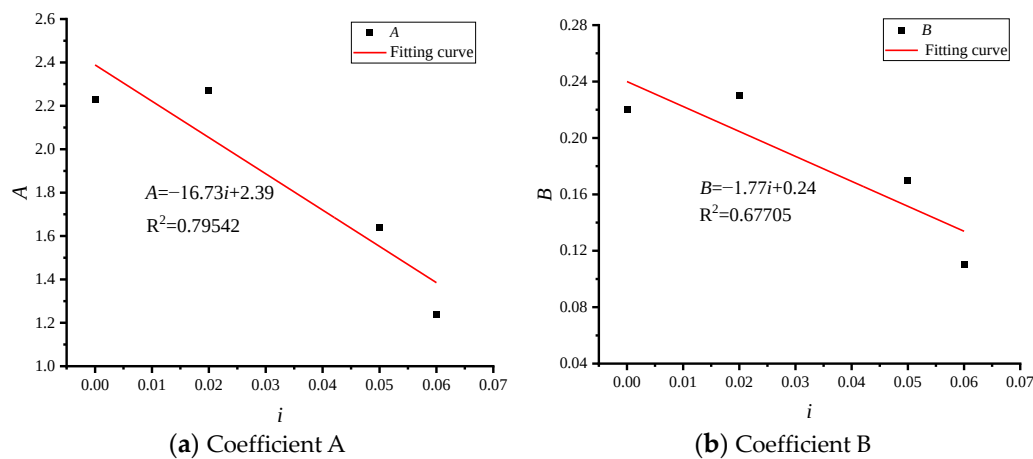


Figure 9. Fitting coefficients A and B.

Therefore, $\frac{\Delta T_{\max,di}}{\Delta T_{\max,i}}$ can be expressed as Equation (8):

$$\frac{\Delta T_{\max,di}}{\Delta T_{\max,i}} = (-16.73i + 2.39)Q_d^{*(-1.77i+0.24)} \quad (8)$$

Figure 10 presents the temperature data calculated using Equation (8) juxtaposed with the experimental temperature data obtained from the experiment, along with comparisons to the experimental data reported by Li et al. [28]. The error falls within 20%, as illustrated in Figure 10. Thus, Equation (8) is capable of predicting the dimensionless maximum temperature rise beneath the ceiling when the fire source is positioned in the near-field region across various integrated common services tunnel slopes.

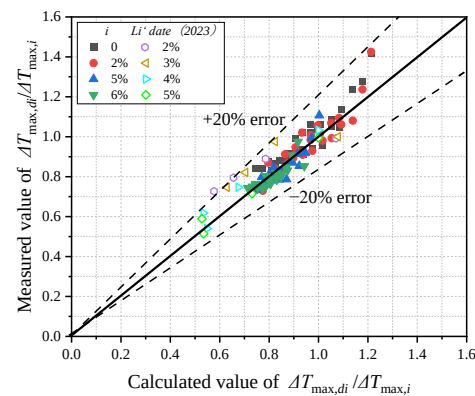


Figure 10. Comparison of calculated values and experimental data.

4. Conclusions

In this study, a 1/10 reduced-scale model tunnel with one end closed was constructed to investigate the maximum temperature profiles on the tunnel's ceiling during a fire. The heat release rates (HRRs) and tunnel slopes (0%, 2%, 5%, and 6%) were varied, and the horizontal temperature in the longitudinal direction beneath the ceiling was measured. The temperature distribution patterns beneath the ceiling during fires in tunnels with different slopes were analyzed. A dimensionless model for predicting the maximum temperature rise, accounting for the influence of tunnel slope, was developed. The main conclusions are as follows:

The maximum temperature beneath the ceiling initially remains stable as the distance from the fire source center to the closed end of the tunnel decreases. It then decreases

and finally increases. Additionally, milder tunnel slopes correspond to higher maximum temperatures beneath the ceiling.

The findings reveal that the distribution of maximum temperatures within a one-end-closed tunnel can be categorized into three distinct regions: far-field ($d/h \geq 3.43$), transition ($2.27 \leq d/h \leq 3.43$), and near-field regions ($d/h \leq 2.27$).

By using dimensional analysis, two prediction models were developed to forecast maximum temperatures beneath the ceiling for fire sources located in the far-field and near-field regions, respectively. These predictive models were validated against experimental data, showing favorable agreement. Due to limited experimental data in the transition region, this paper does not analyze this region. Future experiments could be conducted to explore the fire development patterns in the transitional area.

Author Contributions: Conceptualization, L.L. and G.W.; methodology, G.W. and Z.W.; software, H.H.; validation, H.H. and H.Z.; formal analysis, H.Z.; investigation, L.L.; resources, L.L.; data curation, G.W.; writing—original draft preparation, G.W.; writing—review and editing, Z.W.; visualization, Z.G.; supervision, Z.G.; project administration, Z.G.; funding acquisition, Z.G. and L.L. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the National Natural Science Foundation of China (52076198), the Science and Technology Research Program of Chongqing Municipal Education Commission (KJZD-K202300713) and Excellent Youth Foundation of Henan Scientific Committee (222300420078).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data that support the findings of this study are available upon request from the corresponding author (G.Z.).

Conflicts of Interest: Huixian Huang is employed by the State Grid Chongqing Electric Power Company. The authors declare no conflicts of interest.

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