Research on the Characteristics of Fire Smoke Layer in Cable Compartment of Utility Tunnel

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

Abstract—**The vertical position of the smoke layer within the cable compartment of a utility tunnel plays a pivotal role in governing the dynamics of smoke emission. Given the scarcity of existing research in this area, the present study utilizes numerical simulation experiments based on a full-scale model to explore fire behavior within the cable compartment. Various factors, including the heat release rate (HRR), the dimensions of the cable compartment, and the location of the fire source, are systematically varied. Temperature distributions at specified measurement points within the cable compartment of the utility tunnel are meticulously documented and subjected to comprehensive data analysis. The findings indicate that as the HRR within the cable compartment of the utility tunnel escalates, the height of the smoke layer diminishes. Conversely, as the height of the cable compartment increases, the average height of the smoke layer exhibits a gradual increase, demonstrating a linear relationship. However, as the width of the cable compartment expands, the average height of the smoke layer decreases progressively. This study offers significant insights into the longitudinal dissemination characteristics of thermal smoke within the cable compartment of a utility tunnel during a fire incident.**

Index Terms—**Smoke layer, Fire characteristics, Utility tunnel, Cable compartment**

I. INTRODUCTION

In recent years, the proliferation of cable tunnels in urban areas has been a notable trend [1][2]. However, the cable compartments located within these urban tunnels accommodate a diverse array of electrical materials, rendering them vulnerable to fire occurrences, especially at the cable joints. The swift dissemination of smoke within these compartments presents a considerable hazard, ultimately resulting in substantial economic repercussions in the aftermath of fire incidents [3].

A significant number of academic inquiries have been conducted into the fire protection measures pertaining to cable compartments within utility tunnels. Considering that cable fires constitute a primary hazard within these compartments, a considerable amount of research has been dedicated to evaluating the risks associated with cable combustion. Researchers have sought to understand the behavior of fire within utility tunnels by employing small-scale model experiments and numerical simulations. Thibert et al. [4] conducted an analysis of cable combustion performance using a cone calorimeter, uncovering challenges in predicting the combustion characteristics of diverse flame-retardant cable types. Baker et al. [5] performed physical fire tests based on the actual structural dimensions of utility tunnels, focusing on the horizontal arrangement of power cables according to typical installation practices. This study obtained flame retardant data for cables in utility tunnels, which resulted in significant smoke production and flame spread. Yan et al. [6] carried out numerical simulation studies on the temperature field in L-shaped corridor fire accidents. Zhao et al. [7] examined temperature profiles within small-scale cable tunnels through fire experiments, highlighting accelerated temperature increases in curved utility tunnel sections exceeding 45 ℃. Liang et al. [8] employed numerical simulations to analyze ceiling temperatures in T-shaped corridors under various ignition conditions. Huang et al. [9] explored vertical cable tray fires within confined spaces, proposing a temperature prediction model to assess fire risks in nuclear facilities. Plumecocq et al. [10] developed a semi-empirical model for horizontal cable tray fires in nuclear power plants. Beji et al. [11] conducted numerical simulations on cable tray fires, noting potential underestimations in heat release rate estimates when using cone calorimetry data. Bai et al. [12][13] conducted an extensive series of studies on cable compartment fires in utility tunnels, yet limited attention has been given to investigating the vertical distribution of the thermal smoke layer within these compartments. Notably, under conditions of natural open ventilation in cable tunnel shafts, thermal smoke is observed to propagate longitudinally within the cable compartments during fire incidents. The height of the thermal smoke layer emerges as a crucial parameter influencing fire behavior in these compartments.

A multitude of studies have been undertaken to assess the height of the thermal smoke layer, with a distinct

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concentration on scrutinizing the characteristics of smoke flow within tunnel environments. Chow et al. [14] proposed two techniques for determining the elevation of the thermal smoke layer, which were based on vertical temperature gradients and sudden changes in particle trajectories. Zhang et al. [15] introduced and compared three deterministic models for estimating the position of the smoke layer interface in fire simulations within channels, with a focus on the one-dimensional evolution of the smoke layer interface's attributes. Luo et al. [16] utilized a scaled-down experimental setup to investigate the influence of heavy rainfall on smoke dispersion and stratification dynamics during tunnel fires. Zhang et al. [17] systematically examined the effects of ambient pressure and tunnel inclination on temperature distribution and smoke movement in full-scale tunnel fires under natural ventilation, elucidating the interplay between these factors. Guo et al. [18] constructed a reduced-scale (1:10) tunnel with four shafts to study the dissemination of fire smoke in a naturally ventilated tunnel featuring large cross-sectional roof openings. A series of fire tests were conducted to explore the impacts of fire heat release rate (HRR), shaft height, and shaft spacing on smoke temperature and backflow length. Yi et al. [19] conducted numerical simulations to analyze backflow length in inclined tunnels with vertical shafts by varying tunnel slope, vertical shaft height, and fire source location. The height of the thermal smoke layer has emerged as a pivotal area of research in tunnel fire studies, with significant implications for fire safety in cable compartments within utility tunnels. These parameters are also crucial in the fire protection of cable compartments in utility tunnels [20][21]. It is worth noting that there are distinctions between tunnels and cable compartments within utility tunnels: cables are installed in cable compartments, whereas tunnels do not contain cables. However, the phenomenon of thermal smoke flow stratification differs considerably between fires occurring in cable compartments of utility tunnels and those in tunnels. Therefore, it is imperative to ascertain the height of the thermal smoke layer in fires within cable compartments of utility tunnels under various influencing factors.

The aim of this study is to investigate the optimal smoke layer height necessary for the deployment of temperature sensors and smoke detectors within the cable compartment of a utility tunnel, specifically in the context of a cable fire scenario. Numerical simulation experiments were conducted, employing a full-scale model to simulate fire events within the cable compartment of a utility tunnel. These experiments systematically varied multiple parameters, including HRR, the width and height of the cable compartment, and the position of the fire source. Temperature variations at predefined measurement points within the cable compartment were meticulously documented and subjected to comprehensive data analysis. Furthermore, this article delves into the dynamics of smoke layer height fluctuations during the longitudinal dispersion of thermal smoke within the cable compartment, particularly during the initial stages of a fire, while considering various influencing factors. Ultimately, the findings of this study provide valuable insights that can contribute to advancements in fire protection technology research and the design of fire suppression systems specifically tailored to cable compartments.

II. METHOD

A. Physical Model

The Building and Fire Research Laboratory (BFRL) at the National Institute of Standards and Technology (NIST) has created a software named FDS for simulating fire scenarios. This software employs numerical solutions to a series of Stokes equations that characterize low-velocity thermally induced flows, with particular emphasis on the heat transfer mechanisms and smoke dispersion in fire events. In terms of temporal and spatial discretization, FDS utilizes a second-order explicit prediction-correction approach. The numerical techniques used for discretization and solution are outlined in Reference [22].

As illustrated in Fig. 1, a rectangular cross-sectional configuration with dimensions of 2.6 m in width and 3.0 m in height has been established as the standard for the cable compartment within the utility tunnel. This standardization enhances the applicability of the simulation results. To balance computational efficiency and minimize processing time, the length of the cable compartment in the utility tunnel has been set at 100 m, which is deemed sufficient to achieve the objectives of this study. Additionally, to mitigate the potential influence of boundary conditions on the fire source positioned at the end of the cable compartment, a distance of 50 meters has been maintained between the fire source and the terminal end of the compartment.

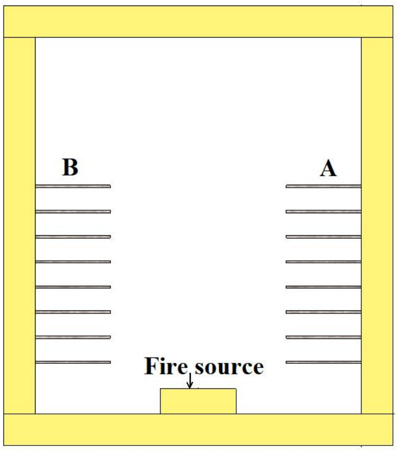

Fig. 1. Physical model of cable compartment in utility tunnel

When determining the placement of temperature measurement points, it is recommended to establish one such point every 1 meter along the centerline, positioned at a depth of 0.2 m beneath the ceiling of the cable compartment within the utility tunnel. This arrangement allows for the measurement of temperature variations beneath the ceiling. Additionally, temperature measurement points should be set every 1 meter from the side wall to monitor temperature changes along the sidewall.

Two sets of simulations, each comprising 14 groups with 48 cases in total, were conducted. In Series 1, the fire source was positioned on the longitudinal centerline of the cable compartment within the utility tunnel, 50 m away from the end face. In Series 2, the fire source was located beneath the lowest cable tray on the A side of the tunnel, also 50 m from the end face. The cable compartment's height ranged from 2.2 m to 4.8 m, and the utility tunnel's width varied between 2.2

m and 3.2 m. The equivalent diameter referred to the diameter of a circle with an area equivalent to the fire source's area. The length of the fire source was calculated based on typical tunnel fire scenarios and used to assess whether the flame would reach the ceiling of the cable compartment. Using the formula for average flame height [23], the HRR was determined. Table 1 presents the simulated operating conditions for the cable compartment length near the fire source in the utility tunnel. N-heptane was selected as the fuel, with a fire source size of a 1 m × 1 m square oil pool. All other parameters were set to their default values in the software.

TABLE 1 FIRE SIMULATION CASES OF CABLE COMPARTMENT IN UTILITY TUNNEL

Series	Case	HRR（kW）	Tunnel Height（m）	Tunnel Width（m）	Flame Length (m)
1, 2	1	250	3	2.6	1.53
	2	500			2.01
	3	800			2.39
	4	1000			2.70
	5	1500	3	2.6	3.16
	6	2000			3.69
	7	2500			3.95
	8	3000			4.35
	9	2000	4.2	2.6	3.69
	10	2000	3.8		3.69
	11	2000	3.4		3.69
	12	2000	2.6		3.69
	13	2000	2.2		3.69
	14	1000	2.2	2.6	2.70
	15	1500			3.16
	16	500			1.60
	17	2500			3.95
	18	3000			4.35
	19	1000	3	3.2	2.70
	20	1000		2	2.70
	21	2000		3.2	3.69
	22	2000		2	3.69
	23	3000		3.2	4.35
	24	3000		2	4.35

B. *Theoretical Analysis*

For the test conditions near the sidewall, this paper uses the Zukoski [20] mirror model to modify the HRR of cable fire sources:

$$H = 0.235Q^{2/5} - 1.02D \tag{1}$$

where, H is average flame height, m; Q is heat release rate, kW; D is the equivalent diameter of the fire source, m.

III. RESULTS AND DISCUSSIONS

A. *Effect of fire source power on smoke stratification*

(1) Location of fire source at longitudinal centerline

To investigate the adverse effects of fire intensity on evacuation processes, this research focuses on analyzing temperature variations and smoke stratification phenomena across different levels of fire intensity. Within the scope of smoke distribution within the cable compartment of a utility tunnel, it is observed that the temperature of the smoke decreases progressively, resulting in decreased buoyancy and subsequent lowering of the smoke layer. This phenomenon is visually illustrated in Fig. 2. Notably, when the fire intensity is set to 250 kW, there is a negligible difference in the smoke layer height at distances of 5 m and 10 m from the fire source. However, at a distance of 30 m from the fire source, the smoke layer's height is 0.20 m lower than at a distance of 20 m, falling below the average eye level of a human (1.80 m).

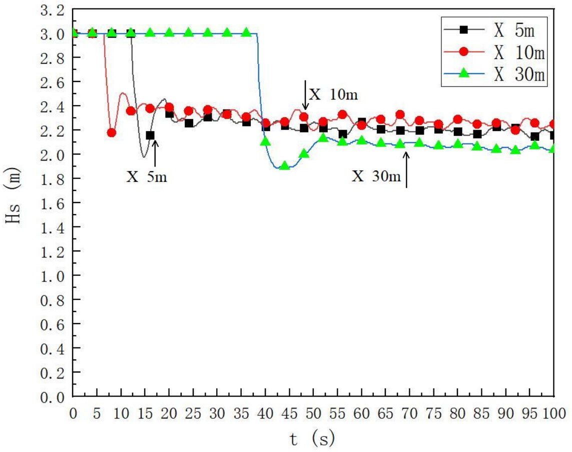

Fig. 2 Variation of height of flue gas layer with time when fire source power is 250 kW

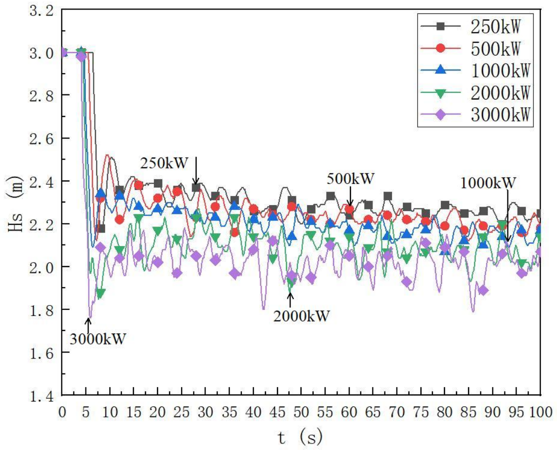

Fig. 3 Variation of height of flue gas layer with time when X = 5 m

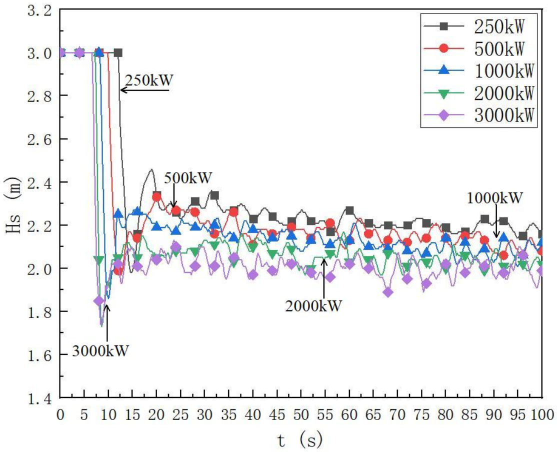

Fig. 4 Variation of height of flue gas layer with time when X = 10 m

The stratification of smoke at various HRRs is analyzed in Figs. 3 ~ 5. Specifically, Fig. 3 illustrates the smoke layer height at a distance of 5 m from the fire source, Fig. 4 depicts the smoke layer height at 10 m, and Fig. 5 shows the smoke layer height at 30 m. A consistent pattern emerges, as the HRR increases, the smoke layer height decreases. Notably, when the HRR exceeds 2000 kW, the smoke layer height drops below the average human eye level of 1.80 m. Additionally, as the distance from the fire source increases, the smoke layer height rises, and for a given HRR, the thickness of the smoke layer diminishes.

Fig. 6 presents an analysis of the mean height of the smoke layer at varying distances from the fire source, across different HRRs. The data indicates that the smoke layer height diminishes as the HRR increases. Furthermore, the smoke layer height decreases as the distance from the fire source augments.

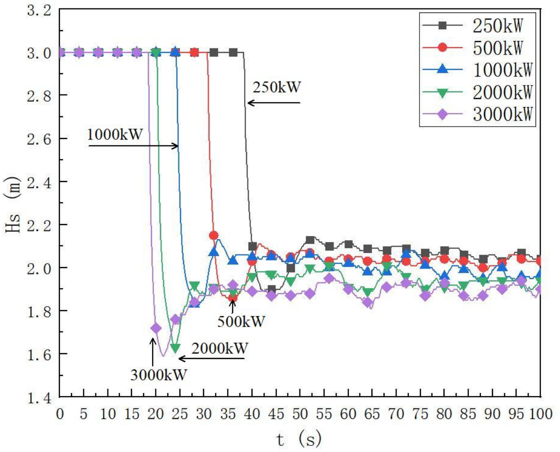

Fig.5 Variation of height of flue gas layer with time when X = 30 m

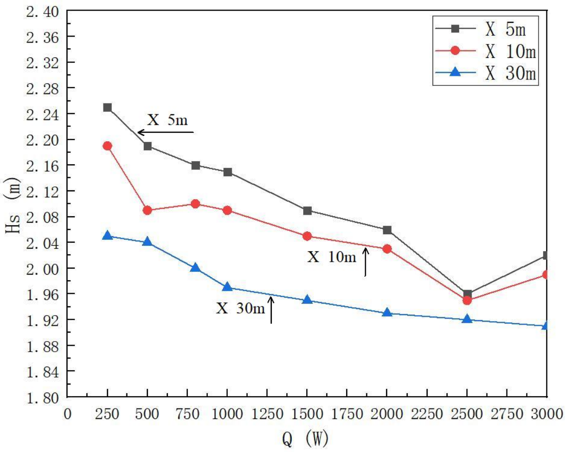

Fig. 6 Variation of average smoke layer height with HRR

(2) Location of fire source on near-wall side

To further elucidate the adverse impacts of .HRR on human evacuation, an analysis of temperature and smoke stratification was conducted when the fire source was positioned on the A side. As illustrated in Fig. 7, the results indicate minimal variation in the smoke layer height between 5 m and 10 m from the fire source when the HRR is 250 kW. Specifically, at a distance of 10 m from the fire source, the smoke layer is merely 0.10 m higher than it is at a distance of 30 m. Notably, the smoke layer height at this distance exceeds the typical human eye level of 1.80 m. These findings underscore the influence of HRR on smoke behavior and distribution in fire scenarios, offering crucial insights for the formulation of effective evacuation plans and safety measures.

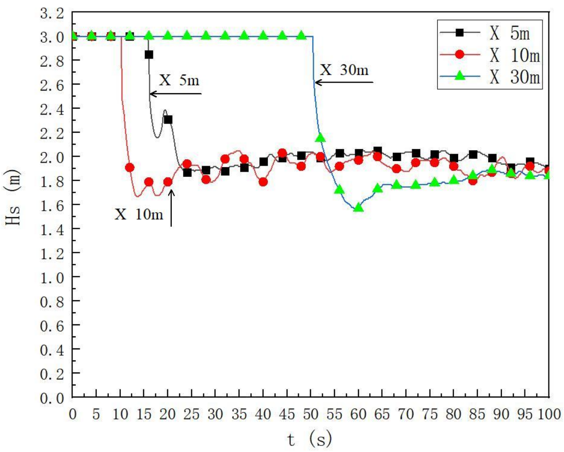

Fig. 7 Variation of height of smoke layer with time when HRR is 250 kW

Figs. 8 ~ 10 provide an analysis of smoke stratification at varying fire source powers. Specifically, Fig. 8 depicts the height of the smoke layer at a distance of 5 m from the fire source, Fig. 9 illustrates the smoke layer height at 10 m, and Fig. 10 shows the smoke layer height at 30 m. A notable trend emerges: as the HRR increases, the height of the smoke layer decreases. When the HRR surpasses 2000 kW, the smoke layer height drops below the average human eye level of 1.80 m. Additionally, as the distance from the fire source increases, the smoke layer height rises, while the thickness of the smoke layer diminishes for a constant HRR.

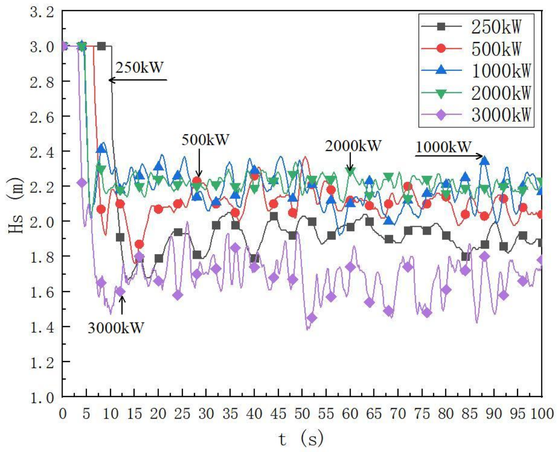

Fig. 8 Variation of height of flue gas layer with time when X = 5 m

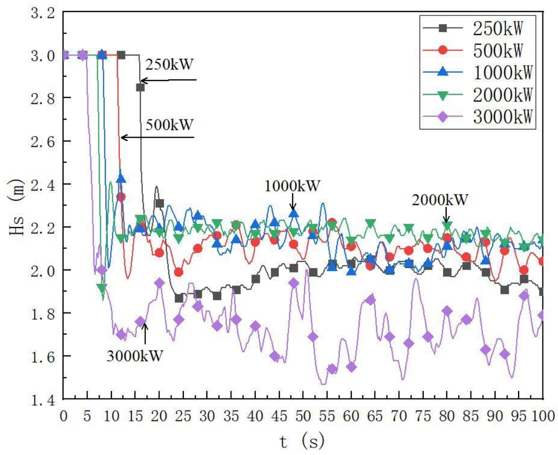

Fig. 9 Variation of height of flue gas layer with time when X = 10 m

Fig. 11 presents an analysis of the mean height of the smoke layer at various distances from the fire source, across different HRRs. The data reveals a tendency for the smoke layer height to initially increase and then decrease as the HRR escalates. Furthermore, the height of the smoke layer exhibits a gradual decline as the distance from the fire source increases.

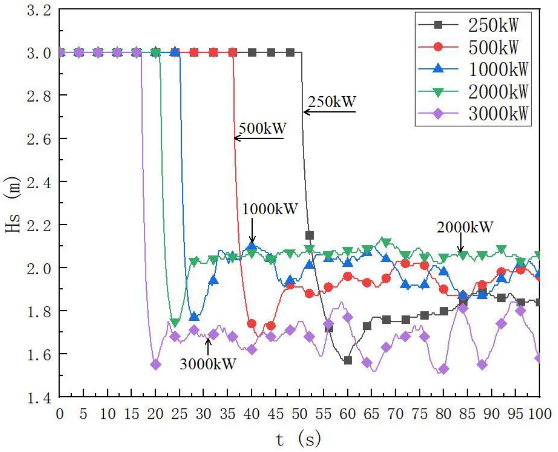

Fig. 10 Variation of height of flue gas layer with time when X = 30 m

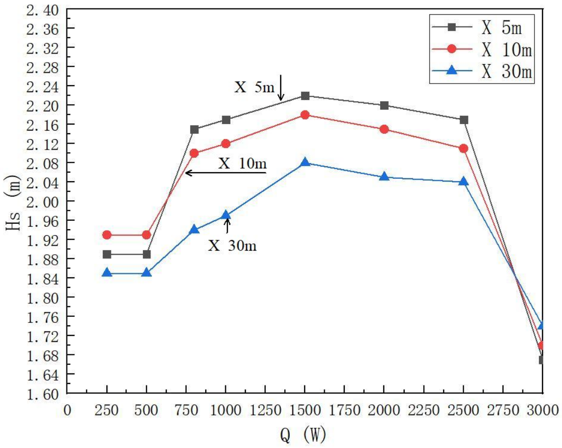

Fig. 11 Variation of average smoke layer height with fire source power

B. Effect of cable compartment height on smoke stratification

This study investigates the influence of cable compartment height on smoke stratification, focusing specifically on the positioning of the fire source both along the longitudinal centerline and independently on the A-side.

(1) Location of fire source at longitudinal center line

Fig. 12 presents an assessment of the relationship between the average smoke layer elevation and the cable compartment height, considering a heat release rate of 2000 kW. As the cable compartment height increases, a gradual and corresponding enhancement in the average smoke layer thickness is observed, indicating a linear correlation. Additionally, it is noted that the average smoke layer height decreases as the distance from the fire source grows.

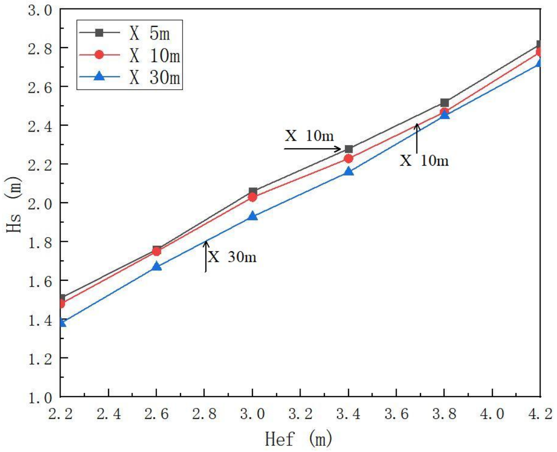

Fig. 12 Variation of average smoke layer height with cable cabin height when HRR is 2000 kW

(2) Location of fire source on near-wall side

Fig. 13 examines the correlation between the average smoke layer height and the cable compartment height, with HRR of 2000 kW. As the cable compartment height augments, there is a gradual increase in the average smoke layer thickness, demonstrating a linear relationship. Furthermore, the average smoke layer height diminishes as the distance from the fire source increases.

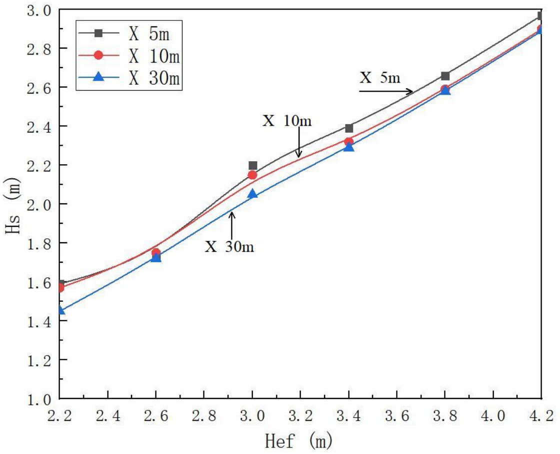

Fig. 13 Variation of average smoke layer height with cable cabin height when fire source power is 2000 kW

As illustrated in Fig.s 12 and 13, when the HRR of the fire source is 2000 kW, the average smoke layer height is significantly influenced by the height of the cable compartment, whereas its dependence on the distance from the fire source is relatively minor.

C. Effect of cable compartment width on smoke stratification

An investigation was conducted to assess the impact of cable compartment width on smoke stratification, with specific attention given to the positioning of the fire source, both along the longitudinal centerline and independently on the A-side.

(1) Location of fire source at longitudinal center line

Fig. 14 presents an analysis of the changes in mean smoke layer elevation with respect to the width of the cable compartment, across various HRRs. At an HRR of 1000 kW, a gradual increase in mean smoke layer elevation is observed as the width of the cable compartment expands. It is noteworthy that the average smoke layer height decreases as the distance from the fire origin increases. In contrast, for fire sources with HRRs of 2000 kW and 3000 kW, a reduction in mean smoke layer height is seen as the width of the cable compartment widens. Consistently, the average smoke layer elevation diminishes as the distance from the fire source augments.

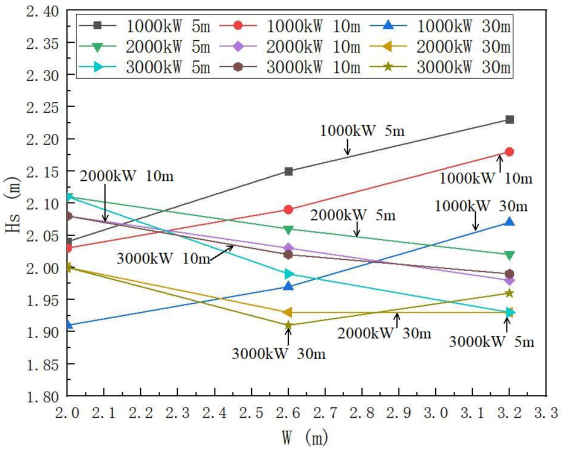

Fig. 14 Variation of average smoke layer height with cable cabin width

(2) Location of fire source on near-wall side

Fig. 15 presents an analysis of the variations in average smoke layer height with respect to the width of the cable compartment, considering different fire source powers when the fire source is positioned on the A-side. At the HRR of 1000 kW, an initial rise followed by a decline in the average smoke layer height is observed as the width of the cable compartment increases. It is notable that the average smoke layer height decreases as the distance from the fire source grows. Conversely, at the HRR of 2000 kW, the average smoke layer height remains relatively stable with an increase in cable compartment width. Similarly, a reduction in the average smoke layer height is seen with an increase in distance from the fire source. Finally, when the HRR reaches 3000 kW, the average smoke layer height exhibits an initial decrease, followed by an increase, as the width of the cable compartment expands.

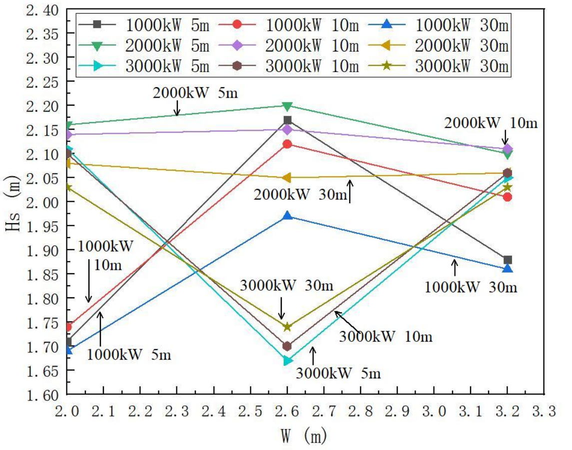

Fig. 15 Variation of average smoke layer height with cable cabin width

IV. CONCLUSIONS

This article investigates the influence of multiple parameters, including the HRR of the fire source, as well as the dimensional attributes of the cable compartment, on the behavior of the smoke layer during a fire event within a cable compartment of a utility tunnel. The fire source is situated along the longitudinal centerline and specifically positioned on the A-side of the cable tray. The primary findings of this study are summarized as follows:

(1) As the HRR of the fire source within the cable compartment of a utility tunnel increases, a corresponding decrement in the smoke layer height is observed. Furthermore, as the distance from the fire source expands, the smoke layer height progressively diminishes. Notably, when the HRR of the fire source exceeds 2000 kW, the smoke layer height descends below the human eye level. At a constant HRR, an increase in distance from the fire source results in an elevation of the smoke layer height but concurrently leads to a reduction in the smoke layer's thickness.

(2) Within the cable compartment of a utility tunnel, the average height of the smoke layer demonstrates a linear increase with an augmentation in the height of the cable compartment. Additionally, as the distance from the fire source increases, a corresponding decrease in the average height of the smoke layer is noted.

(3) As the width of the cable compartment expands, the average smoke layer height gradually decreases. Specifically, when the fire source is located on the A-side and the HRR is 1000 kW, the average smoke height exhibits an initial rise followed by a decline. Notably, an increase in distance from the fire source leads to a corresponding decrement in the average height of the smoke layer. Alternatively, at an HRR of 2000 kW, the average height of the smoke layer remains relatively stable as the width of the cable compartment increases. Conversely, at an HRR of 3000 kW, the average smoke height initially decreases and then increases with an augmentation in the width of the cable compartment within the utility tunnel.

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