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A Whole Process Prediction Method for Temperature Field of Fire Smoke in Large Spaces

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Abstract

Based on the fire development model for the whole process of localized fires in large-space buildings and assisted by the technology of FDS large eddy simulation, the temperature fields of fire smoke of localized fires in large spaces were investigated with different building heights, building areas and fire powers. It has been found that for large-space buildings with a height greater than 6 m and a building area more than 1500 m^2, factors like building height and building area can slightly affect the curve trend of fire smoke, while such factor like fire power has more significant influence on the curve trend of fire smoke. Through the analysis of temperature rise curves of fire smoke in various fire scenarios, the paper proposed a whole-process prediction model for the temperature fields of fire smoke of localized fires in large-space buildings. As long as the model uses the appropriate shape coefficient, the prediction model can accurately predict the temperature fields of fire smoke of localized fires in large-space buildings.

Keywords: localized fire, smoke temperature, large eddy simulation fire development

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Nomenclature

T_g	smoke temperature (℃)
T	fire duration (min)
Q	heat release rate (kW)
$Q_{\max}$	maximum heat release rate of the fire (kW)
t_d	time when the fire enters the decay phase (s)
T_m	maximum temperature of fire smoke at a certain location under the ceiling during the fire (℃)
T_0	initial environment temperature (℃)
$T_g^{\max}$	maximum value of fire smoke temperature at the ceiling right above the fire source(℃)
A	building area (m^2)
H	building height (m)
D	diameter of the fire source (m)
Greek symbols	
k_{sm}	temperature correction coefficient
x	horizontal distance from the center of the fire source (m)

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α	growth coefficient (kW/s^2)
ϖ_1	curve shape coefficients of fire smoke during the development phase
ϖ_2	curve shape coefficients of fire smoke during the decay phase
η	correction coefficient

1. Introduction

The existing prediction methods for the smoke temperature in a fire are mainly concentrated in predicting the temperature distribution of fire smoke in an enclosure room fire. For general enclosure fires, the temperature distribution is more uniform, and regional models are often used for analysis of smoke temperature. Currently, the temperature standard curves, such as ISO 834 curve, ASTM-E119 temperature curve, External fire temperature curves and Hydrocarbon temperature curve are commonly used for fire resistance analysis of structures and these curves are all obtained from experiment data of enclosure fires [1-5]. Wherein ISO 834 temperature curve is the most commonly-used and most representative temperature curve for fire resistance analysis of fire scene structure, and it can be represented as:

$$T_g = 345\log(8t+1)+20$$

From above equation it can be found that the smoke temperature reaches 659℃ 10 minutes after the fire breaks out, and reaches 821℃ 30 minutes after the fire breaks out. However, for localized fires in large spaces, due to large building volume and building height, the building interior naturally forms a place which is suitable for smoke and heat storage, and the heat generated by the fire does not accumulate quickly, thus resulting in relatively slow temperature rise of hot smoke in the fire scene [6]. In addition, localized fires in large-space buildings have adequate oxygen supply, and such fires belong to fuel-control type combustion, so flashover is rare and the smoke temperature in the fire scene generally does not exceed 600℃. Secondly, unlike the relatively uniform temperature distribution in enclosure room fires, the smoke temperature fields in localized fires in large-space buildings features a non-uniform distribution. The farther the ceiling is away from the centerline of fire source, the lower smoke temperature is, so the basic assumption of an uniform smoke temperature fields in enclosure room fires does not apply to the smoke temperature fields in localized fires in large spaces [7]. To predict the smoke temperature fields in localized fires in large-space buildings, we need to fully consider the non-uniform distribution of fire smoke temperature in the fire scene. In summary, the smoke temperature fields in large-space localized fires are significantly different from that of enclosure fires [8]. But till now researches on the smoke temperature fields of localized fires in large-space buildings are still very scanty.

Moreover, unlike the standard fire curve, a natural fire is characterized by three phases: a growing phase, a full developed phase and a decay phase. It is necessary to evaluate not only the heat effect on the structural resistance during the heating phase, but existing studies focused on the smoke temperature development in growing phase and full developed phase, while few studies have been conducted on the temperature development in the decay phase of a fire.

In order to study the temperature fields of fire smoke during the whole process of localized fires in large-space buildings, this paper, based on the inductive analysis of temperature rise curve of fire smoke, this study proposed a temperature rise model of fire smoke for predicting the whole process of localized fires in large spaces. The comparison of results respectively from the model predictions and large eddy simulation shows that, the prediction model can accurately predict the temperature fields of fire smoke of localized fires in large spaces.

2. Large Eddy Simulation of Fire smoke Temperature of Localized Fires in Large Spaces

2.1. Fire Development Model

A typical localized fire in a large space generally experiences its development phase, steady phase and decay phase. The development model for the whole process of localized fires in large spaces as follows:

$$Q = \alpha t^2 \qquad 0 \le t \le t_g$$

$$Q = Q_{\max} \qquad t_g \le t \le t_d$$

$$Q = \frac{t_s}{t_s - t_d} Q_{\max} - \frac{t}{t_s - t_d} Q_{\max} \qquad t_d \le t \le t_s$$

2.2. Large Eddy Simulation of Fire smoke Temperature of Localized Fires

In order to study the distribution law of the temperature fields of fire smoke in fire scenes with different fire powers, different building areas and building height, a series of full-scale fire experiments need to be carried out for demonstration. Performing dozens of full-scale fire experiments is not only costly and difficult to operate, but also can cause environment pollution, and furthermore, the experiment results are often affected by experiment environment and laboratory instruments. The FDS fire smoke simulation technology based on large eddy simulation technology has increased the potential to solve such problems. FDS fire smoke simulation analysis technology is applied based on the FDS software platform which is a professional software launched by NIST for fire smoke migration analysis. The software uses spatial filtering method for a simplified manipulation of Navier-Stokes equations, and the simplified equation shares some features with elliptic partial differential equations, which makes itself suitable for simulating the flow processes of low-speed fire smoke migration and heat convection. When it comes to localized fires in large-space buildings, the problems of heat and mass transfer in FDS model fit the basic models of fluid dynamics [9,10].

3. Temperature Fields of Localized Fires in Large Space

Using FDS large eddy simulation technology, this study investigated the distribution of temperature fields of fire smoke in tens of fire scenes with different building heights (6 m~12 m), building areas (1,500 m^2~10,000 m^2) and fire powers (2MW-25MW). Therein the heat release rate per unit area of the fire is set as 500kW/m^2, and the simulated fire duration is 2h. The simulation results showed that in spite of different temperature rise curves of fire smoke for various fire scenes, the overall variation trend of the temperature rise curves of fire smoke are identical and follows a certain rule. For large-space buildings with a height greater than 6 m and a building area more than 1500 m^2, the building height and building area has relatively little effect on the curve trend of fire smoke, while the power of fire source can significantly influence the curve trend of fire smoke.

3.1. Basic Equations

By observing and analyzing flue temperature rise curves of localized fires in large spaces, the study established the prediction model of the temperature fields of fire smoke for the whole development process of localized fires:

$$T_g = T_m \times e^{-(\ln t - \ln t_d)^2/\varpi_1} + T_0 \qquad t \le t_d$$

$$T_g = T_m \times e^{-(\ln t - \ln t_d)^2/\varpi_2} + T_0 \qquad t \ge t_d$$

In the prediction model of temperature fields of fire smoke during the whole development process of localized fires in large spaces, the maximum fire smoke temperature T_m and curve shape coefficients of fire smoke, ϖ_1 and ϖ_2 are two leading factors in determining the development curve of fire smoke. Fig 1 shows how different maximum values of fire smoke temperatures influence the curves of fire smoke with identical ϖ_1, ϖ_2, t_d and T_0. Fig 2, on the other hand, shows how different shape coefficients influence the curves of fire smoke with identical T_m, t_d and T_0; as seen in Fig 2, the shape coefficients ϖ_1 and ϖ_2 have determined the shapes of the temperature curves of fire smoke. The greater ϖ_1 is, the faster the fire smoke temperature rises; the greater ϖ_2 is, the slower the fire smoke temperature drops.

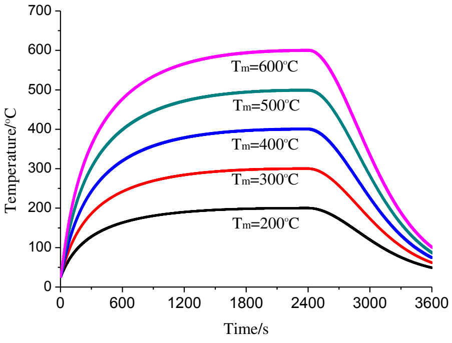


Fig. 1. Effect of maximum temperatures on the temperature rise curves (with identical ϖ_1, ϖ_2 and T_0)

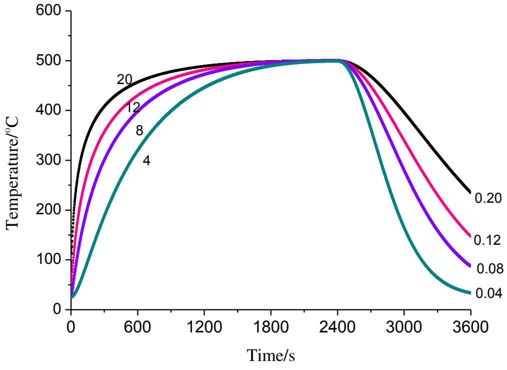


Fig. 2. Effect of shape coefficients on the temperature rise curves (with identical t_m and T_m T_0)

3.2. Maximum Value of Fire Smoke Temperature

As shown in Fig 3, when a localized fire breaks out in a large space, the fire smoke rises under the influence of thermal buoyancy and spreads around. Fig 4 is a typical temperature section of fire smoke layer below the ceiling; from Fig 4 it can be seen that the temperature of the fire smoke layer gradually decreases outward along the fire source, the fire smoke temperature reaches its maximum at the plume centreline, and fire smoke temperatures are relatively uniformly distributed within a certain range around the plume centreline (inside the black circle in Fig 4), and furthermore, the fire smoke temperatures away from the fire source show a significant decreasing trend . Therefore, the flue temperatures below the ceiling exhibit a non-uniform distribution, and the temperature of fire smoke is correlated with factors such as the power of the fire source, building characteristics, and the horizontal distance between fire smoke and the centre of the fire source.

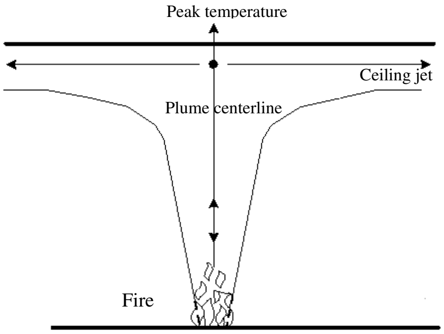
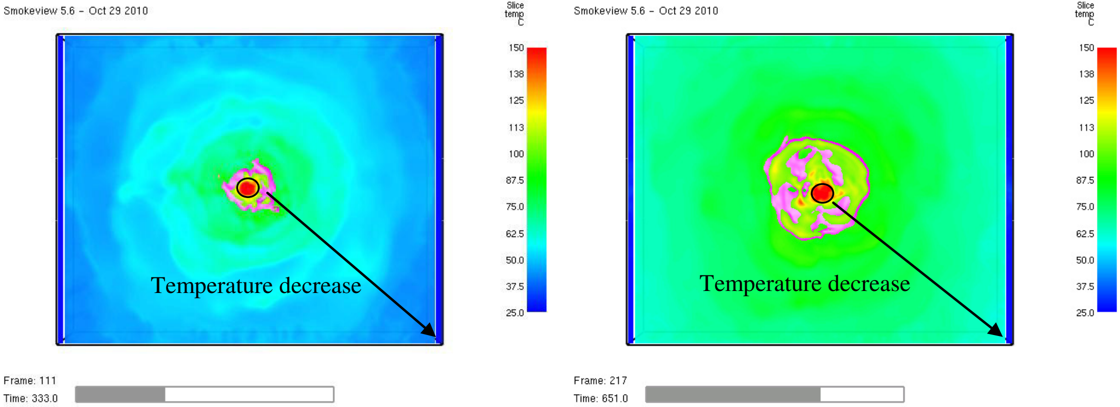


Fig. 3. Fire smoke migration in a localized fire



333 s after the fire breaks out

651 s after the fire breaks out

Fig. 4. Vertical section of fire smoke temperature of a typical building fire in a large space

Professor Du Yong from Nanjing University of Science and Technology in China studied the maximum value of the temperature field of fire smoke inside the building for a 2~25MW fire in a large-space building with a height of 4~20 m and an area of 500~600 m^2. It has been found that the maximum value of the temperature of fire smoke at a location below the ceiling can be expressed as [11]:

$$T_m = T_g^{\max} \times k_{sm}$$

$T_g^{\max}$ is dependent upon the factors such as fire power, building height and building area. It has been found from Professor Du's fitting analysis of the data that:

$$T_g^{\max} = (Q_{\max}/50+80)-(4Q_{\max}/10000+3)H+(52Q_{\max}/1000+598)\times 10^2/A$$

The temperature correction coefficient k_{sm} is correlated with the horizontal distance between fire smoke and the center of the fire source, Professor Du has presented the empirical equation of the temperature correction coefficient:

$$k_{sm} = \eta + (1-\eta)e^{(D/2-x)/7} \qquad x \ge D/2$$

$$k_{sm} = 1 \qquad x \le D/2$$

And $D=\sqrt{\frac{4Q}{\pi q}}$. η is the correction coefficient which depends upon the factors of building height and area, as shown in Table 1.

Table 1. Value for η

Building area (m^2)	Building height (m)				
	6	9	12	15	20
500	0.60	0.65	0.70	0.80	0.85
1000	0.50	0.55	0.60	0.70	0.75
3000	0.40	0.45	0.50	0.55	0.60
6000	0.25	0.30	0.40	0.45	0.50

3.3. Shape Coefficient

Shape coefficient is key to determining the temperature curves of fire smoke. After the simulation analysis of fire scenarios with different fire powers, building heights and building areas, the author found that for large-space buildings with a height greater than 6 m and a building area more than 1500 m^2, building height and building area have exerted relatively little impact on the shape coefficient, whereas the power of fire source can significantly influence the value of the shape coefficient. Based on the inductive analysis of the temperature curves of fire smoke in different fire scenarios, the author proposed the recommended values of the shape coefficients for a localized fire with wooden combustibles in a typical large-space building (the fire development coefficient is 0.0346 kW/s^2). For fire power of less than 5MW, the recommended value of shape coefficient at the development phase and the steady phase of the fire is 8, and that at the decay phase is 0.08. For fire power of 5MW~25MW, the recommended value of shape coefficient at the development phase and the steady phase of the fire is 6, and that at the decay phase is 0.08.

3.4. Case Study

A localized fire broke out in a large-space building with a height of 12 m and abuilding area of3500 m^2. The fire development coefficient is 0.0346 kW/s^2, the heat release rate per unit area is 500 kW/m^2, and the maximum heat release rate is 16MW. The fire lasted for 2 h and the ambient temperature is 25℃. The temperature variation curve of fire smoke for the ceiling at a distance of 10 m from the center of the fire source needs to be determined.

First, we can decide on the fire development model:

$$Q=0.0346t^2 \qquad 0\le t\le 680$$

$$Q=16000 \qquad 680\le t\le 2551$$

$$Q=54909-15.25t \qquad 2551\le t\le 3600$$

Then we can determine the maximum value of the fire smoke temperature at the ceiling right above the fire source:

$$T_g^{\max}=(16000/50+80)-(4\times 16000/10000+3)\times 12+(52\times 16000/1000+598)\times 10^2/3500=328$$

we can further determine the temperature correction coefficient k_{sm}:

$$k_{sm}=0.6+(1-0.6)\times e^{(6.38/2-10)/7}=0.751$$

Where, the diameter of the fire source $D=\sqrt{\frac{4Q}{\pi q}}=\sqrt{\frac{4\times 16000}{\pi\times 500}}=6.38$ m.

Therefore, the maximum value of the fire smoke temperature for the ceiling at a horizontal distance of 10 m from the centre of the fire source during the whole process of the fire is:

$$T_m=T_g^{\max}\times k_{sm}=328\times 0.751=246.4$$

Since the fire power is 16 MW, the shape coefficient at the development phase and the steady phase of the fire is recommended as 6, and the shape coefficient at the decay phase is recommended as 0.08. The temperature reaches its maximum at 2551 s, and the ambient temperature is 25 ℃. Thus, the temperature rise curve of fire smoke for the ceiling at a distance of 10 m from the centre of the fire source can be represented as follows:

$$T_g=246.4\times e^{-(\ln t-\ln 2551)^2/6}+25 \qquad t\le 2551$$

$$T_g=246.4\times e^{-(\ln t-\ln 2551)^2/0.08}+25 \qquad t\ge 2551$$

4. Conclusion

Based on the fire development model for the whole process of localized fires in large-space buildings and assisted by the technology of FDS large eddy simulation, the temperature fields of fire smoke of localized fires in large spaces were investigated with different building heights, building areas and fire powers. It has been found that for large-space buildings with a height greater than 6 m and a building area more than 1500 m^2, factors like building height and building area can slightly affect the curve trend of fire smoke, while such factor like fire power has more significant influence on the curve trend of fire smoke. Through the analysis of temperature rise curves of fire smoke in various fire scenarios, the paper proposed a whole-process prediction model for the temperature fields of fire smoke of localized fires in large-space buildings. As long as the model uses the appropriate shape coefficient, the prediction model can accurately predict the temperature fields of fire smoke of localized fires in large-space buildings.

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