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The Study on Smoke Movement Characteristics and Evacuation of High-Rise Building Stairwells with Multiple Factors

多因素下高层建筑楼梯间烟气运动特性研究

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Abstract

In this study, the method of combining numerical simulation and theoretical analysis is used to study the movement characteristics of smoke in the staircase of a high-rise building. First, the effects of different heat release rates, ambient temperatures, baffles and other conditions on the smoke temperature of the stairwell are studied. Secondly, the effects of different opening heights and ambient wind conditions on the smoke concentration of the stairwell are studied. Finally, the effects of different conditions are studied. The smoke movement is compared with the speed of people climbing stairs. It is found that the heat release rate has little effect on the smoke speed, and the outside wind has a great influence on the smoke speed. When the outside wind is faster than the critical wind, there is no obvious change in the velocity of the hot smoke distribution in the stairwell with various outside wind speed is similar; on the contrary, the speed of the hot smoke decreases with an increase of the outside wind speed. It is hoped that the research results can provide certain theoretical guidance for the safe evacuation of people in the fire stairwell of high-rise buildings, and design a set of reasonable evacuation plans.

Keywords: High-rise building stairwell; Hot smoke; Numerical Simulation; Evacuation

1 Introduction

Nowadays, with the economy growing rapidly and the population increasing, high-rising buildings have become ubiquitous. Although the problem of land demand has been alleviated, it has brought endless safety problems. Increasingly frequent high-rise building fires have caused a large number of casualties, property losses and environmental pollution[1]. There are many vertical shaft structures in high-rise buildings, such as elevator , stairwells, and ventilation ducts. When the fire breaking out, hot smoke may enter the vertical shaft and quickly spread to other areas [2-5]. A large number of fire cases

1 引言

当今世界经济增长迅速，人口不断增长，高层建筑随处可见，缓解了土地需求问题的同时又带来了大量的安全问题，愈发频繁的高层建筑火灾造成了大量的人员伤亡、财产损失以及环境污染[1]。当火灾发生时，热烟气可能会进入垂直竖井快速蔓延到其他区域[2-5]。大量的火灾案例表明烟气对人的威胁是最大的，接近85%的人在火灾中死亡是烟气造成的[6]。因此，研究楼梯间的烟气运动可为人员逃生提供一定理论指导。

在过去的几十年内，许多学者对高层建筑烟气运动情况(包括试验和数值模拟)展开

indicate that nearly 85% of the deaths are caused by smoke from the fire[6]. Therefore, studying the smoke movement in the stairwell during a fire can provide some theoretical guidance for personnel to escape.

In the past few decades, many scholars have carried out research on the smoke movement of high-rise buildings (including experiments and numerical simulations). Marshall[7] used a 1/5 scale model of shaft to study the movement of smoke and proposed an empirical equation for predicting air entrainment in the shaft. Shi et al.[2] used a 1/3 scale model of stairwell to study and found that before the stack effect occurs, turbulent mixing strongly affects the movement of hot smoke. Sun[8] investigated the smoke movement in a 6-story full-scale stairwell and found that the smoke temperature decreased with increasing height in the stairwell. Zhang et al.[9] used Fire Dynamics Simulation(FDS) to numerically simulate the smoke movement in a 90-meter-high building. Li et al.[10] also used FDS to simulate the smoke movement in a 35-meter-high building.

This paper simulates the movement of smoke through different ambient temperature, heat release rate, opening position, ventilation velocity and whether baffles which can delay smoke diffusion are installed or not. Finally, the smoke temperature, smoke concentration and velocity and other data will be measured and analyzed in the case of various conditions. This study aims to find out the smoke movement characteristics of the stairwell in the high-rise building better in the case of various conditions and combine the normal speed of the healthy adults up and down the stairs, which is conducive to the design of reasonable evacuation plans.

2 Numerical Simulation

2.1 Fire Dynamics Simulation (FDS)

FDS is a computational tool based on the Navier-Stokes equations appropriate for low-speed (Ma<0.3). There are two main methods to deal with turbulent flow in FDS: large eddy simulation (LES) method and direct numerical simulation (DNS) method. The governing equations include continuity, species concentration balance, momentum and energy balance, and the ideal gas law [11].

了研究。Marshall[7]利用一个 1/5 尺寸的竖井模型研究了烟气的运动情况，并提出了一个预测竖井内空气夹带的经验方程。Shi[2]等人利用一个 1/3 尺寸的楼梯间模型研究发现在烟囱效应发生前，湍流混合强烈地影响热烟气的运动。Sun[8]通过调查全尺寸的 6 层高楼梯间的烟气运动，发现楼梯间的烟气温度随高度增加而减少。Zhang[9]等人使用火灾动力学模拟软件(FDS)对一个高为 90m 的建筑的烟气运动进行数值模拟。Li[10]等人也使用 FDS 模拟了 35m 高的建筑内的烟气运动。

本论文分别模拟了不同环境温度、热释放速率、开口位置、通风速度以及是否安装挡板情况下的烟气运动。最终测量出各工况下的烟气温度，烟气浓度，烟气速度等数据加以分析。本研究旨在更好的了解高层建筑在各个情况下发生火灾时楼梯间的烟气运动特性，结合健康成年人正常上下楼梯的速度，利于设计合理的人员疏散逃生的方案。

2 数值模拟

2.1 火灾动力学模拟(FDS)

FDS 是一种以纳维-斯托克斯方程为基础的适用于低速(Ma<0.3)的模拟软件。FDS 中处理湍流流动主要有两种方法：大涡模拟(LES)方法或直接数值模拟(DNS)方法。控制方程包含了连续性方程、物种浓度平衡、动量平衡、能量平衡以及理想气体状态方程[11]。

2.2 模型

本次数值模拟的工况如图 1 所示。这个 10 层建筑模型尺寸的高为 44m(z 轴)，宽为 8.02m(y 轴)，长为 3.42m(x 轴)。

测点示意图如图 2 所示，在楼梯间的垂直中心线上安装了 43 个热电偶，每个热电偶之间的距离为 1.05m。

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2.2 Model

The working condition of this numerical simulation is shown in Fig. 1. The 10-story building model has a height of 44m (z-axis), a width of 8.02m (y-axis), and a length of 3.42m (x-axis).

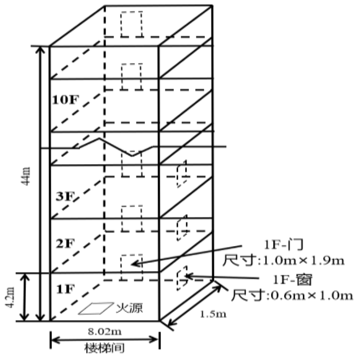
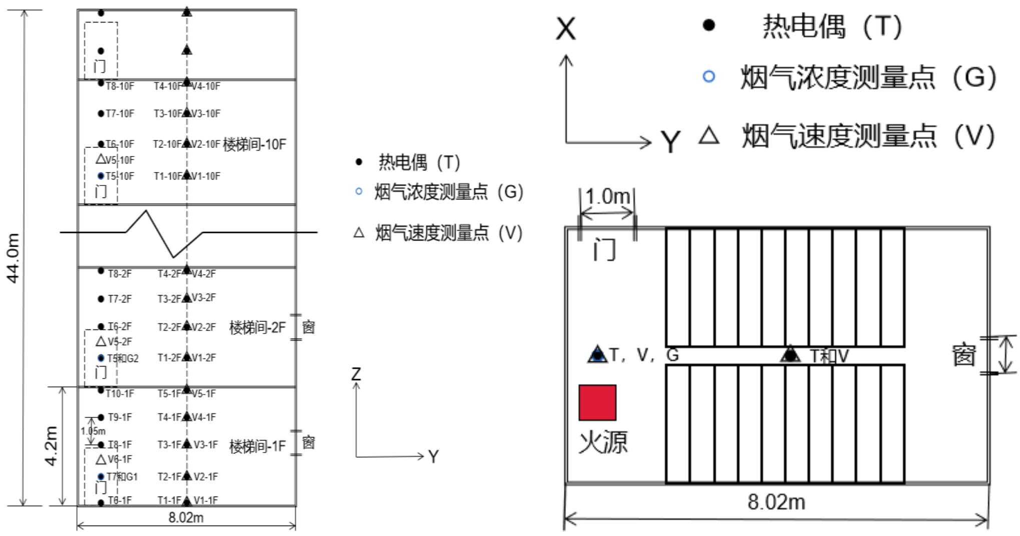


Fig. 1 10-story stairwell model diagram

图 1 10 层高楼梯模型图

The schematic of the measuring point is shown in Fig 2. A total of 43 thermocouples are installed on the vertical centerline of the stairwell and the distance between each one is 1.05m.



(a) (b)

Fig. 2 Thermocouple position, velocity measurement point and somke measurement point. (a) Front view; (b) Top view.

图 2 热电偶位置、速度测点以及烟气测点，(a) 主视图；(b) 俯视图。

3 Results and Discussion

3.1. Influence of different conditions on smoke temperature

Sun et al.[12] proposed the relationship between normalized temperature rise and normalized height as follows:

3 结果与讨论

3.1. 不同条件对烟气温度的影响

Sun 等人[12]提出了归一化温升与归一化高度之间的关系如下所示：

$$\frac{\Delta T}{T_0} = \frac{T - T_0}{T_0} = \alpha e^{-\beta \frac{z}{H}} \tag{1}$$

$$\alpha = \frac{T_f - T_0}{T_0} \tag{2}$$

$$\beta = \frac{AhH}{C_p D \dot{m}_s} \tag{3}$$

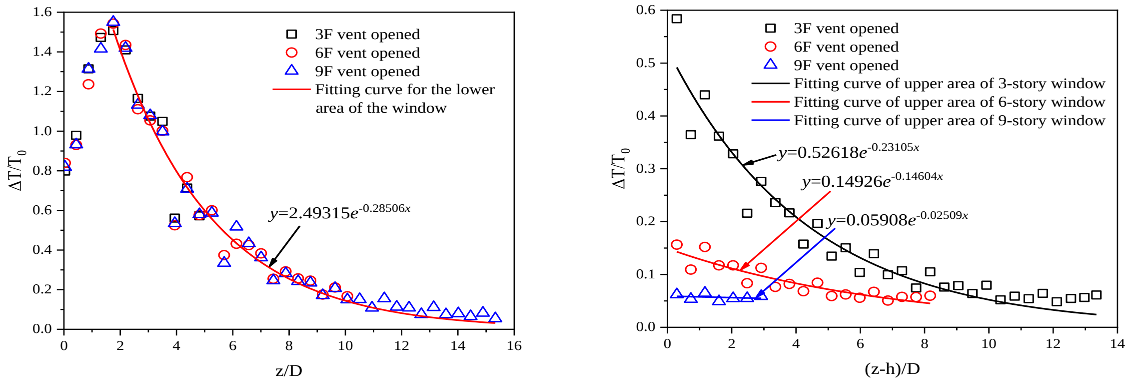
where ΔT is the temperature rise between the hot smoke and ambient air; T is the temperature of hot smoke; T_0 is the temperature of ambient air; α is a constant of the smoke temperature; β is the temperature attenuation coefficient; z is the height above the fire source; H is the height of the stairwell; T_f is the temperature of the smoke plume on the fire floor; A is the horizontal sectional area of the stairwell; h is the convective heat transfer coefficient between hot smoke and the inner walls; D is the hydraulic diameter of the stairwell, and $\dot{m}_s$ is the mass flow rate in the stairwell. In the numerical simulation conducted in this study, the height H in Eqs. (1) is replaced with the hydraulic diameter D of the stairwell, which is given by:

其中 ΔT 是热烟气与初始环境温度之间的温升；T 是热烟气的温度；T_0 是初始环境温度；α 是热烟气温度的常数；β 是温度衰减系数；z 表示火源上方高度；H 表示楼梯间高度；T_f 是热烟气在地板上的温度；A 是楼梯间水平截面面积；h 表示热烟气与楼梯间内壁之间的对流换热系数；D 表示楼梯间的水力直径；$\dot{m}_s$ 表示楼梯间内的质量流量。本研究中将(1)式中的 H 替换成水力直径 D，其表达式如下：

$$D = \frac{L \times W}{2(L + W)} \tag{4}$$

where L is the length (8.02m) and W is width (3.42m) of the stairwell. Therefore, Eqs. (1) can be rewritten as

$$\frac{\Delta T}{T_0} = \frac{T - T_0}{T_0} = \alpha e^{-\beta \frac{z}{D}} \tag{5}$$



(a) (b)

Fig. 3 The relationship between the normalized temperature rise and the normalized height of the stairwell with windows opened on different floors. (a) Lower region; (b) Upper region.

图 3 不同开窗情况下楼梯间归一化温升与归一化高度的关系。(a) 下部区域；(b) 上部区域。

Fig. 3 shows the relationship between the normalized temperature rise $(T\text{-}T_0)/T_0$ and the normalized height (z/D) with the conditions of different single-layer window opened, and the temperature data is fitted using Eqs. (10). As shown in Fig. 3, in the lower region, the temperature data of different opening heights can be fitted with a curve, which shows that the opening height has little effect on the temperature distribution of the hot smoke in the lower region. On the contrary, for the upper region, the temperature data of different opening heights cannot be fitted with a curve, and after fitting, it is found that as the opening height increases, the fitting curve gradually becomes slower.

Fig. 4 shows the relationship between the normalized temperature rise $(T\text{-}T_0)/T_0$ and the normalized height (z/H) of the stairwell and use Eqs. (1) to fit the temperature data. Due to the special structure of the stairwell, the smoke moves upward spirally so that the vertical temperature on the longitudinal centerline in the stairwell drops rapidly.

图 3 展示了不同单层开窗情况下归一化温升$(T\text{-}T_0)/T_0$与归一化高度(z/D)的关系，利用(10)式进行温度数据的拟合。如图 3 所示，在较低的窗户下部区域，不同开口高度的温度数据可以用一条曲线拟合，这说明开口高度对开口下部区域的热烟气温度分布影响不大。而对于较高的窗户上部区域，不同开口高度的温度数据不能用一条曲线拟合，且经过拟合后发现随着开口高度的增加，拟合曲线逐渐变缓。

图 4 显示了楼梯间的归一化温升（$T\text{-}T_0$）$/T_0$ 与归一化高度(z/H)的关系，利用(1)式对温度数据进行拟合。由于楼梯间的特殊结构使得烟气呈螺旋向上运动，因此楼梯间内纵向中心线上的垂直温度迅速降低。

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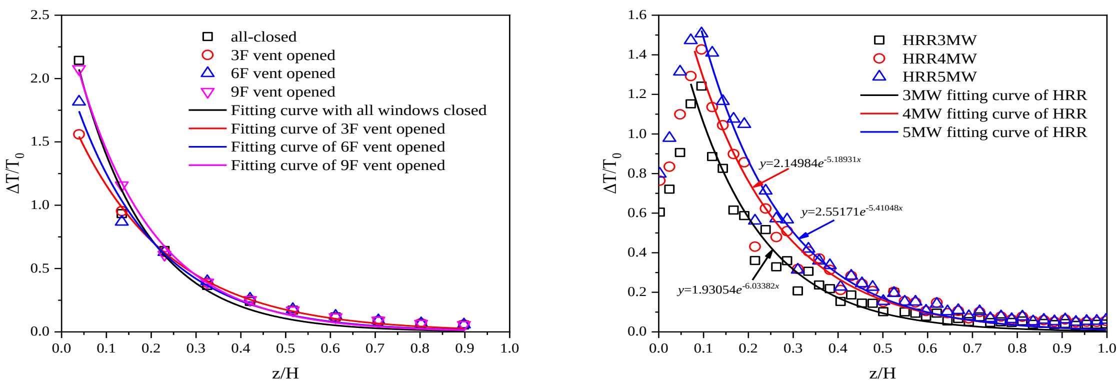

(a) (b)

Fig. 4 The relationship between normalized temperature rise and normalized height of staircases with different conditions. (a) Different opening positions; (b) Different HRR

图 4 不同条件楼梯间归一化温升和归一化高度的关系。(a) 不同开口高度；(b) 不同热释放速率

Table 1 summarizes the fitting values of α and β with different conditions, where R^2 is the Pearson correlation coefficient between the simulated data and the fitted curve, and its value range is 0 to 1. The larger value of R^2, the better the fit. All the values of R^2 in Table 1 exceed 0.95 indicating that the accuracy of the fitting is reliable. The value of β represents the attenuation coefficient of temperature. According to Table 3, β increases as the opening height increases with the same condition, while β did not show a monotonous increase or decrease with the increase of the heat release rate of the fire source.

表 1 总结了不同条件下的 α 和 β 的拟合值，其中 R^2 是表示模拟数据与拟合曲线之间的皮尔逊相关系数，其取值范围为 0～1，R^2 越大说明拟合的越好，表 1 中所有的 R^2 值都超过了 0.95，说明拟合的准确性是可靠的。β 值代表了温度的衰减系数，根据表 3 可知，在相同的条件下，β 值随着开口高度的增加而增加。随着火源热释放速率的增加，β 值没有呈现单调增加或减少现象。

Tab. 1 Fitting values of α and β with different conditions

表 1 不同条件下 α 和 β 的拟合值

Variables	**Closed**	**Opened vents**			**Heat Release Rate**		
		3F	6F	9F	3MW	4MW	5MW
α	2.66407	1.85303	2.15254	2.57763	1.93054	2.14984	2.55171
β	6.45806	4.71496	5.44817	5.83637	6.03382	5.18931	5.41048
R^2	0.983	0.9983	0.98289	0.99583	0.957	0.966	0.975

3.2. Influence of different conditions on smoke concentration

Fig. 5 shows the distribution of CO concentration on stairwell with different conditions. It can be seen from Fig. 5(a) that the CO concentration of the stairwell has a similar decreasing trend and

3.2. 不同条件对烟气浓度的影响

图 5 显示了不同条件下楼梯间 CO 浓度情况。从图 5(a)可以看出楼梯间 CO 浓度下降趋势相似且 1 层 CO 浓度相近。除此之外未在楼

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the CO concentration of the first floor is similar. In addition, the CO concentration of floors where the baffles are not installed on the side of the stairwell step is higher than that of the baffles installed indicating that the installation of the baffles on the side of the stairwell step can achieve effect of preventing smoke and reduce the concentration of smoke appropriately. From Fig. 5(b), it can be seen that the decreasing trend of CO concentration on each floor with different opening positions is similar and the value of them is approximate. The main reason for the reduction of the effect of the opening is that the small opening causes not enough smoke to be discharged and fresh air enters the stairwell to increase the smoke generation as well as the scale of the entire stairwell is larger than the opening. It can be seen from Fig. 5(c) that the CO concentration of each floor in the stairwell is significantly reduced. The CO concentration on the 3rd floor in the stairwell is higher than that on the 2nd floor when all windows are open and without air supply, however, when all windows are open and the air supply speed is 2m/s and 3m/s, the CO concentration of the 4th floor in the stairwell is higher than that of the 3rd floor. Below the 5th floor, the CO concentration of all windows closed is higher than that of all windows open (except for the first floor where the air supply speed is 3m/s) and the higher theair supply speed, the higher the CO concentration. The main reason may be the competition between the amount of smoke produced by combustion and the amount of smoke discharged from the windows because of the supply of air. On one hand, the ambient wind accelerate the upward spiral movement of the smoke, and on the other hand, it also accelerate the discharge of the smoke from the windows, however, the overall amount of smoke generated is less than the amount of smoke discharged from the windows which makes the CO concentration when all windows are open less than all windows closed. Above the 5th floor, the CO concentration of all windows opened is higher than that of all windows closed. Because of the supply of air, the smoke spirals up and reaches the upper level of the stairwell faster. Compared with the smoke rising from the bottom of the stairwell, the amount of exhausting from the window is less, resulting in the CO concentration decreases slower and higher than the condition of all windows opened.

梯间台阶侧边安装挡板的CO浓度要比安装挡板的高，说明在楼梯间台阶侧边安装挡板对1层CO浓度的影响很小，而高于1层时可以起到一定的挡烟隔烟效果，适当降低了烟气的浓度。从图 5(b)可以看出不同开口高度下各楼层CO浓度下降趋势相似且数值相差不大，这主要是因为开口较小，排出的烟气不够多且有新鲜空气从外界进入楼梯间增加了烟气的产生，并且整个楼梯间的尺寸远大于开口尺寸，最终导致单开口的影响作用变小。从图 5(c)可以看出楼梯间各楼层的 CO 浓度降低。在全窗打开且无送风的工况中楼梯间内 3 层CO浓度高于2层，而送风速度为2m/s和3m/s的工况下则是楼梯间 4 层 CO 浓度高于 3 层。当楼梯层数小于5层时，全窗关闭的 CO 浓度高于全窗打开(除送风速度为 3m/s 的 1 层外)且送风速度越大CO浓度越高，这可能是因为燃烧产生的烟气量与窗户排出烟气量之间的竞争，一方面送风加快了烟气向上螺旋运动，另一方面也加快了烟气从窗口的排出，但总体产生的烟气量小于从窗户排出的烟气量，使得开窗送风下的CO浓度低于全窗关闭；当楼梯层数大于5层时全窗打开的 CO 浓度高于全窗关闭，这是因为存在送风，使得烟气螺旋上升运动加快，烟气可以更快到达楼梯间上层，虽然也有烟气从窗口排出，但少于从底部上来的烟气量，使得CO浓度的下降变缓且高于全窗关闭。

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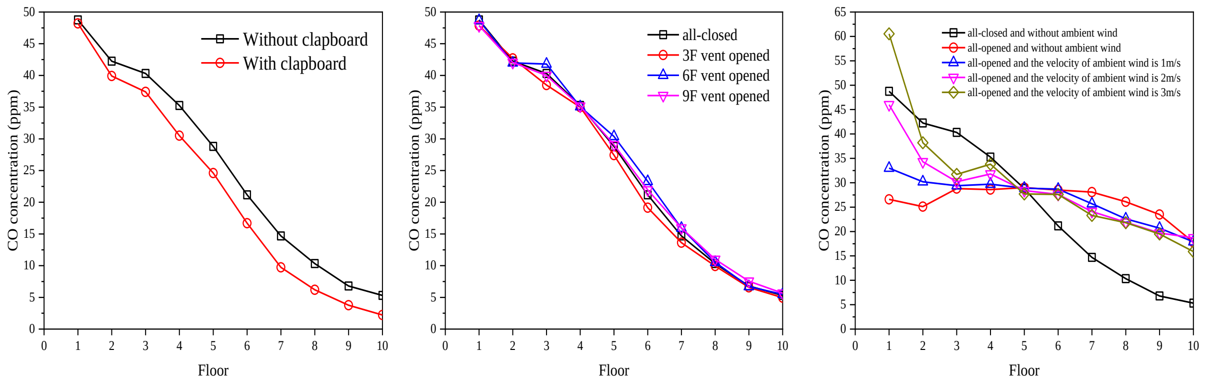

(a) (b) (c)

Fig. 5 Distribution of carbon monoxide concentration in stairwell floors with different conditions. (a) With baffle and without baffle; (b) Different opening positions; (c) Different wind speed.

图 5 不同条件下楼梯间楼层 CO 浓度分布。(a)有无挡板；(b)不同开口高度；(c)不同风速。

3.3. Influence of different conditions on smoke velocity

The distribution of smoke velocity on stairwell floors with different conditions is shown in Fig. 6. From Fig. 6(a), it can be seen that the smoke velocity with baffles is faster than that without baffles and the smoke velocity is gradually reduced without baffles, however, with baffles, it first increases and then decreases and the maximum velocity then decreases and the maximum velocity appears on the 2nd floor. From Fig. 6(b), it can be seen that the smoke velocity of window opening is faster than that of all windows closing, and the smoke velocity of different opening positions is almost the same, indicating that the opening of the vent in the stairwell is beneficial to increase the smoke velocity rather than the opening positions. From Fig. 6(c), it can be seen that the smoke velocity of the 2nd to 3rd floor is increasing with the conditions of no air supply and 1m/s air supply while the situation is opposite when the air supply speed is 2m/s and 3m/s. Below the 4th floor, the higher the air supply speed, the faster the smoke velocity. On the contrary, the higher the air supply speed above the 4th floor, the lower the smoke speed and the difference between the air supply speed of 2m/s and 3m/s is inapparent. There is a critical air supply speed between the air supply speed of 1m/s and 2m/s. When the air supply speed is slower than the critical speed, the smoke velocity changes significantly, however, when the air supply speed is faster than the

3.3. 不同条件对烟气速度的影响

图 6 显示了不同条件下楼梯间楼层烟气速度的分布情况。从图 6(a)可以看出有挡板的烟气速度大于无挡板且无挡板的烟气速度逐渐降低，而有挡板却是先增加后降低，最大速度出现在 2 层。从图 6(b)可以看出窗户打开的烟气速度大于关闭的速度且不同开口高度的烟气速度几乎相同，说明楼梯间内有通风口打开可以增加烟气速度但开口的高度对烟气速度的影响很小。从图 6(c)可以看出当无送风和送风速度为 1m/s 时，2 层到 3 层的烟气速度是上升的，而送风速度为 2m/s 和 3m/s 是下降的。在 4 层以下时送风速度越大烟气速度越大，而 4 层以上送风速度越大烟气速度越小且送风速度为 2m/s 和 3m/s 差异很小，说明送风速度为 1m/s 和 2m/s 之间存在临界送风速度，当送风速度大于临界速度时，烟气速度几乎相同。全开窗的 4 种条件下烟气速度在 7 层及 7 层以下大于成年人跑步上楼速度，而在 8 层及 8 层以上则小于成年人跑步上楼速度，因为窗户全部打开和送风加快了热

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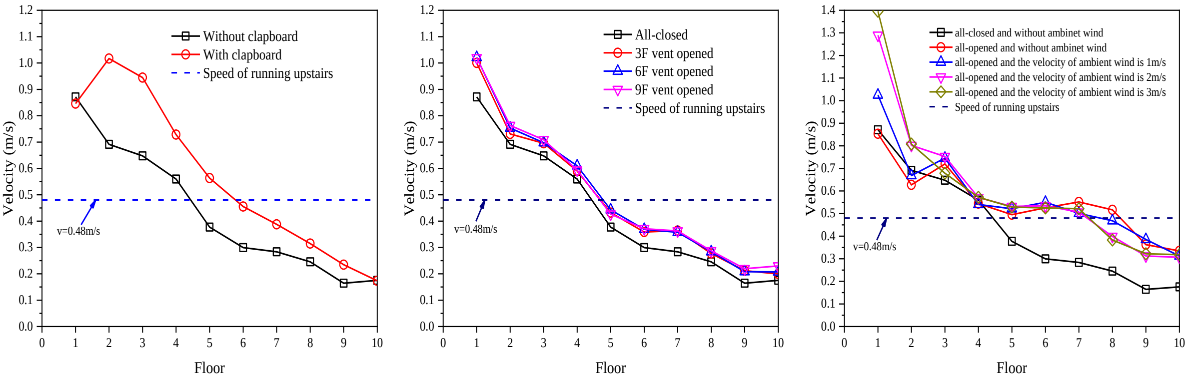
critical speed, the smoke velocity is almost the same. Below the 7th floor, the smoke velocity is faster than that of adults running upstairs when all the windows are opened. Above the 8th floor, the smoke velocity is slower than that of adults running upstairs with the same conditions. It is very dangerous to evacuate because the condition of all the windows opening and the air supply accelerates the movement of the hot smoke.

烟气的运动，说明此情况下是十分危险的，非常不利于人员疏散撤离。



(a) (b) (c)

Fig. 6 Smoke velocity distribution of stairwell floors with different conditions. (a) With baffle and without baffle; (b) Different opening positions; (c) Different wind speed.

图 6 不同条件下楼梯间楼层烟气速度分布

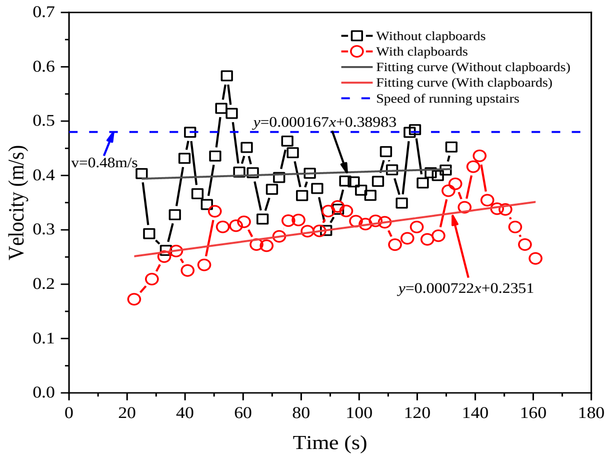


Fig. 7 Smoke velocity in stairwell with baffle and without baffle

图 7. 有无挡板楼梯间烟气速度

With different conditions, the change of smoke velocity in the stairwell with time is shown in Fig. 7. From Fig. 7 it can be seen that the speed of running upstairs is almost faster than the speed of smoke without baffles and with baffles within 2 minutes. People can move up to 57.6m, which is higher than the height of the 10-story stairwell indicating that the installation of baffles on the side of the stairwell steps can reduce the smoke velocity to a certain extent and delay the spread of hot smoke. Therefore, residents can safely evacuate to the top of the building within 2 minutes and wait for rescue.

4 Conclusions

In this study, a series of numerical simulations of a full-scale stairwell were carried out. The conclusion is as follows:

(1) With different conditions, the temperature rise trend is similar. When the opening is opened, the smoke temperature rise in the stairwell can be divided into two areas: the lower region and the upper region. The hot smoke in the lower region is mainly affected by the stack effect and turbulent mixing. On the contrary, in the upper region, turbulent mixing is the main reason for the hot smoke.

(2) Below the 5th floor, the CO concentration increases with air supply speed increasing; Above the 5th floor, the CO concentration is little affected by the air supply speed.

(3) When all the openings are open, there is a critical air supply speed in the stairwell .There is no significant difference when the hot smoke velocity is faster than the critical air supply velocity. On the contrary, the hot smoke velocity decreases with the air supply velocity increasing. Therefore, baffles can be installed in the stairwell to reduce the smoke concentration and some unique ventilation systems can be designed so that the residents can evacuate down from the stairwell or move

图 7 显示了不同条件下楼梯间内烟气速度随时间的变化情况。从图 7(a)可以看出在 2min 内，成年人跑步上楼速度几乎总是高于无挡板的烟气速度，并且无挡板的烟气速度总是大于有挡板，2min 内成年人可以向上运动 57.6m，大于 10 层楼梯间的高度，说明在楼梯间台阶侧边安装挡板后可以一定程度的降低烟气速度，延缓热烟气的蔓延；在 2min 内住户可以安全向上撤离到楼顶等待救。

4 总结

在本研究工作中，进行了一系列的全尺寸楼梯间的数值模拟，总结结论如下：

(1)各条件下的温升趋势相似。当开口打开时，楼梯间的热烟气温升可以分成开口下部区域与上部区域。开口下部区域烟气受到烟囱效应和湍流混合的共同影响，而开口上部区域，湍流混合是影响烟气的主要原因。

(2)在 5 层以下，送风速度越大，CO 浓度越高；在 5 层以上，送风速度的大小对 CO 浓度的影响很小。

(3)楼梯间内存在临界送风速度，在临界送风速度以上，热烟气速度相似，相反热烟气速度随着送风速度增加而减少。因此可以在楼梯间内安装合适的挡板以降低烟气浓度，设计一些独特的通风系统，使高层建筑发生火灾后居民可以更安全地从楼梯间向下疏散撤离或向上转移等待救援。

up to wait for rescue after a high-rise building fire occurs.

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