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A Study on the Impact of Window Partition Walls on the Spread of Fire on Building Facades

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Abstract: This paper investigates the impact of window partition walls on the spread of fire on building facades under the impact of environmental wind through Fire Dynamics Simulator simulation experiments. A four-story building model was constructed using a Fire Dynamics Simulator incorporating six different wind speed conditions and six different partition wall widths. The fire-blocking performance of window partition walls of varying widths was systematically compared and analyzed, and the data indicated: (1) Under calm wind conditions, the installation of window partition walls is observed to facilitate the vertical spread of facade fires. Moreover, as the width of these partition walls increases, this facilitative effect becomes increasingly prominent; (2) Under wind speeds of 0 to 5 m/s, the temperature on the leeward side is lower when window partition walls are present than when they are absent. This indicates that window partition walls inhibit the horizontal spread of building facade fires, and wider window partition walls have better horizontal fire resistance performance.

Keywords: window partition wall; high-rise buildings; FDS simulation; fire spread

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1. Introduction

The acceleration of urbanization and continuous economic growth have significantly increased the urban population density, highlighting the growing role of high-rise buildings in modern urban structures. Along with the increase in the number and height of high-rise buildings, the potential risk of urban building fires also rises. Data from the China National Fire and Rescue Administration indicate a significant increase in high-rise building fire incidents in 2022 compared to previous years. The fire incidence rate rose by 276% from 2021. The impact of facade factors on fire spread in high-rise buildings is multifaceted. It involves various aspects, such as material selection, structural details, layout, and environmental conditions [1]. As shown in Figure 1, designers incorporate many fire-resistant components, like eaves and partition bands during the design process. In actual fire accidents, the geometry of the wall also has an important impact on the fire risk. Figure 2a shows the residential building fire incident that occurred in Ming Shang Xi Yuan, Yuhuatai District, Nanjing on 24 February 2024. The fire was caused by an electric bicycle parked on the first floor catching fire. Because of the wind, the fire spread vertically and horizontally. This incident resulted in 15 deaths and 44 others receiving medical treatment. Figure 2b shows the fire incident at Zhongyi Building in Shijiazhuang, Hebei Province, on 9 March 2023, where the concave walls of the burning building caused the fire to spread rapidly upwards. Case studies of facade fires in buildings demonstrate that facade geometry can impact fire behavior.

(**a**) (**b**)

Figure 1. Exterior building fire protection component. (**a**) Eaves case. (https://www.sohu.com/a/771292546_121342467, accessed on 5 May 2024); (**b**) Partition bands case. (https://co.pinterest.com/pin/351914158382391979/, accessed on 5 May 2024).

(**a**) (**b**)

Figure 2. Cases of high-rise building fires. (**a**) Nanjing fire case. (https://www.thepaper.cn/newsDetail_forward_26440329?commTag=true, accessed on 6 May 2024); (**b**) Hebei fire case (http://www.yongtai.gov.cn/xjwz/ztzl/xfaq/xfxc/202302/t20230221_4540802.htm, accessed on 6 May 2024).

Real-world cases of facade fires in buildings demonstrate that varying facade geometries can influence fire behavior. These geometries alter the flame propagation path and affect the fire spread rate and burning intensity [2]. Therefore, studying the impact of these geometries on fire risk and behavior is crucial.

Both domestic and international scholars have extensively researched facade fires in buildings. Some researchers studied the fire effects of balconies and eaves. For example, Zhang [2] simulated the fire overflow on the balconies, as well as the temperature distribution indoors and outdoors, and proposed fire prevention and extinguishing design schemes for old buildings. Moreover, Zhao [3] conducted experimental research on fire spread, revealing the role of convex fire-resistant eave structures in the spread of flames on building facades. By comparing the temperature distribution in different exterior wall areas, the study explored the differences in the impact of concave, planar, and convex structures on facade flame spread. Additionally, Fang [4] studied the impact of environmental wind speed on the overflow and diffusion behavior of flames at the openings under eaves through Computational Fluid Dynamics simulation. Furthermore, Nilsson et al. [5]

examined how various passive protective measures, such as balconies and window sill walls, influence the vertical spread of fires externally.

Other scholars investigated the effect of the walls between the windows on fire. Hu et al. [6] studied the partition mechanism of wall widths between windows on double-window fire overflow by combining simulation and physical experiment. In addition, Ye et al. [7] conducted a comparative analysis of the effects of the height and layout of the walls between the windows on fire spread under six different working conditions. Later on, Zhao [8] studied the influence of the width of windows and the coupled effect of the length of balcony projection on the fire spread of building facades.

Regarding the effect of side walls on the spread of building fires, Tsai [9–12] investigated the effects of combustible materials in I, L, and concave shapes on flame propagation. Huang et al. [13] studied the combustion rate, flame length, and flame tilt angle of a heptane pool fire positioned behind a baffle in a windy environment. They found that the upper flame tilt angle is primarily influenced by crosswind, while the lower flame tilt angle is affected by crosswind speed, baffle height, and the distance between the baffle and the flame. Shih and Wu [14] investigated the effects of combustible materials in I, II, IIII, L, concave, and W shapes on flame propagation. Moreover, Tian et al. [15] conducted a detailed study on the impact of different shapes of side walls on the temperature distribution of exterior wall windows. Furthermore, Lu [16] studied how the spacing between side walls affects the air entrainment effect of flame overflow at various stages and proposed an entrainment model under different side wall constraint conditions. In addition, Xu et al. [17] measured and analyzed the impact of adjacent parallel side walls, proposing the vertical temperature curve of window jet flames. Adding to that, Fang et al. [18] conducted experiments to investigate how adjacent single sidewalls affect the temperature curve of smoke flow from window jet fires in fire partition walls. Apart from this, Liu et al. [19] investigated how window size, heat release rate, and distance from the sidewall affect the development of average flame height under the constraint of a single sidewall. They developed a flame entrainment model based on the changes in average flame height and flame entrainment features, aiming to illustrate the discrepancy in average flame height between the constrained sidewall boundary and the unrestricted boundary without sidewalls. More recently, Yakovchuk [20] utilized FDS modeling to investigate how external vertical enclosure structures impact fire spread on the surface of exterior wall insulation systems containing combustible insulation layers. Godakandage et al. [21] studied the effect of different geometric shapes of cavity spaces on building flame spread. It is found that the small cavity will accelerate the diffusion of gas pairs, and the corresponding strategies are proposed.

Previous studies on how fire protection structures influence lateral fire spread in high-rise building fires, as indicated by the above research, are limited. Fire spread behavior is governed by the combined effects of thermal buoyancy and wind force. Environmental wind, a significant factor influencing the external facade fire spread of buildings, may cause a horizontal shift in the vertical fire spread path, posing a threat to upper floors and adjacent rooms. Extensive research has been conducted on the influence of material properties on fire behavior, resulting in valuable findings and customization of models for various scenarios. However, there has been limited exploration of the impact of geometric configurations and their impact on building fire safety.

This study aims to contribute to the gap by researching into the geometric property's impacts on fire risks. As a result, in this paper, a simulation study is conducted to investigate how window partition walls affect the spread of building facade fires in office-type buildings. To reach this goal, a numerical experiment was conducted and elaborated in Section 2. Results obtained from this numerical experiment are analyzed and discussed in Section 3. In the end, Section 4 concludes this study.

2. Experiment Design

2.1. Establishing the Numerical Simulation Model

A four-story building model was created using a Fire Dynamics Simulator based on established fire protection features for building facades. The buildings in the model use non-combustible concrete. Each floor consists of two identical rooms, with a column grid measuring 7.8 m × 6.0 m, resulting in room dimensions of 6 m × 3.9 m × 3 m. The distance between windows on the left and right sides is 1 m. The windows above and below are positioned to meet the minimum height requirement of 1.2 m, as specified by regulations, with 0.8 m downstairs and 0.4 m upstairs [22]. The window size is 2.4 m × 1.8 m.

The fire originates on the ground floor. Figure 3 illustrates protruding vertical partitions between horizontally adjacent rooms. Meteorologically, wind speed is the important factor influencing fire propagation, and this study investigates the influence of external environmental wind speed on fire spread. The ambient temperature is maintained at 20 °C.

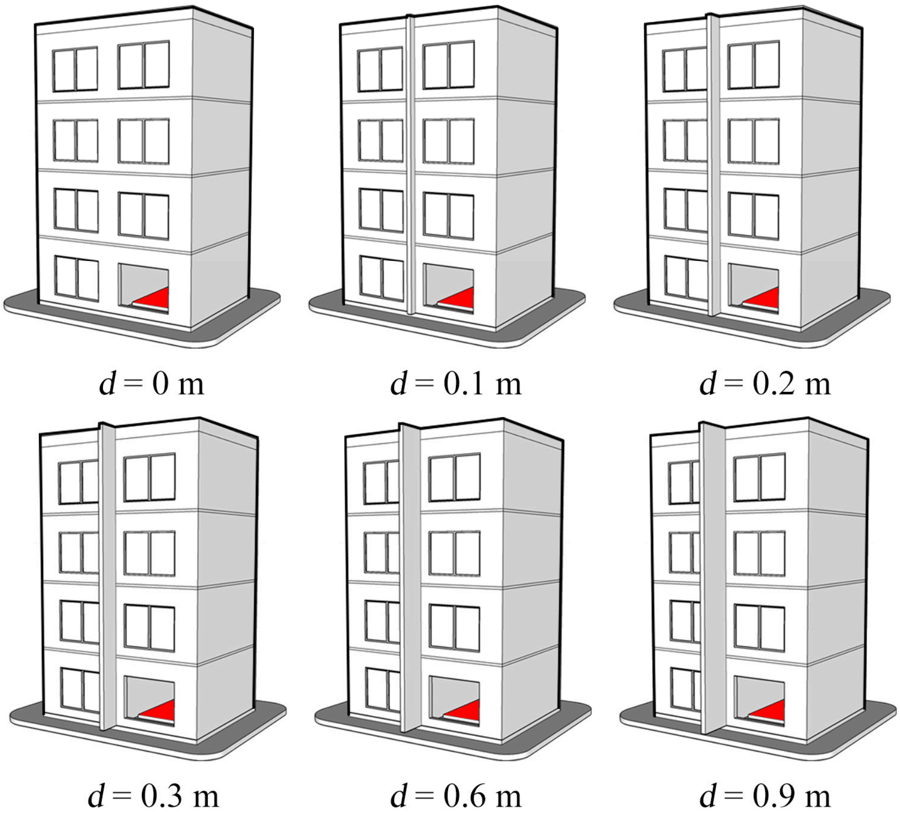
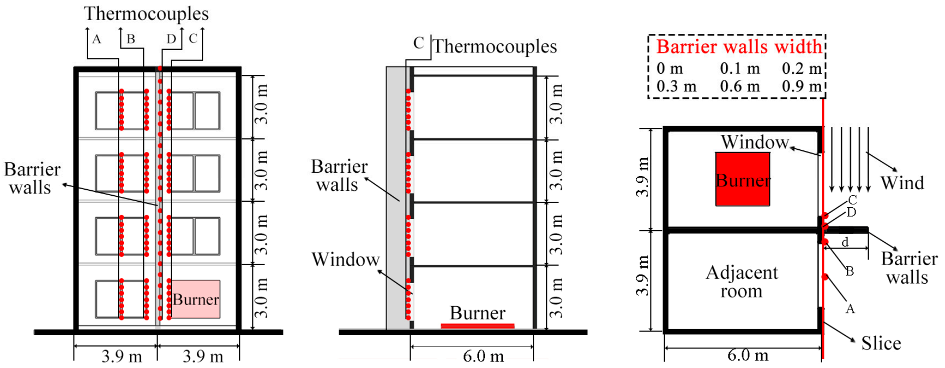


Figure 3. The numerical simulation model.

2.2. Experimental Condition

To conduct the impact of varying wind speeds and window partition wall widths on the spread of facade fires in buildings, six different widths of window partition walls (d) and six environmental wind speeds (v) were selected, resulting in 36 conditions. The six window partition wall widths are labeled as groups W_1, W_2, W_3, W_4, W_5, and W_6. The wind direction used represents the most unfavorable condition, blowing horizontally from the fire floor towards the safe side, as shown in Figure 4c. The experimental conditions are detailed in Table 1.



(**a**) Front view (**b**) Side view (**c**) Top view

Figure 4. Devices and slices layout.

Table 1. Experimental condition.

Group	W_1	W_2	W_3	W_4	W_5	W_6
Width (m)	0	0.1	0.2	0.3	0.6	0.9
Wind speed (m/s)	0	0	0	0	0	0
	1	1	1	1	1	1
	2	2	2	2	2	2
	3	3	3	3	3	3
	4	4	4	4	4	4
	5	5	5	5	5	5

2.3. Devices Layout

As shown in Figure 4, the red circle represents the thermocouple, a total of 109 thermocouples and one temperature slice were arranged. The temperature slice is located on the front facade of the building, parallel and closely adjacent to the wall.

Thermocouple group A is located midway along the leeward-side windows, each window with seven thermocouples arranged vertically in the central axis spaced 0.3 m apart.

Thermocouple group B is located on the right side of the windows on the leeward side, each window with seven thermocouples vertically arranged and spaced 0.3 m apart.

Thermocouple group C is located on the right side of the windows on the fire side, each window with seven thermocouples vertically arranged and spaced 0.3 m apart.

Thermocouple group D is located on the right side of the intermediate partition wall, at the angle between the partition wall and the wall and spaced 0.5 m apart.

Thermocouple groups A and B are employed to measure the temperature distribution on the leeward side-windows. Group C is intended to measure the temperature distribution of windows above the fire-affected side. Group D thermocouples are utilized to measure the temperature distribution at L-shaped wall corners.

2.4. Burner Settings

Currently, widely recognized models for the growth trend of flame power during fire occurrence include experimental fire models, theoretical fire growth models, MRFC models, and models that determine flame growth rates through continuous superposition and mathematical calculations. The fire source power is typically determined based on building codes, using predefined values. The Chinese "Code for Fire Protection Design of Buildings" provides guidelines for the heat release rates of rooms with different functions. It states that external sprinkler systems with quick-response heads can reduce the heat release rate by 40%. Relevant heat release rate data are shown in Table 2 [23], where the heat release rate for office spaces without sprinkler systems is 6 MW.

Table 2. Maximum heat release rate values for typical fire locations.

Typical Fire Locations	Maximum Heat Release Rate/MW
Offices and guest rooms with sprinklers	1.5
Offices and rooms without sprinklers	6.0
Shopping malls with sprinklers	5.0
Public places with sprinklers	2.5
Public places without sprinklers	8.0
Supermarkets and warehouses with sprinklers	4.0
Supermarkets and warehouses without sprinklers	20.0

Currently, most experimental data are obtained using calorimeters, but the effects of boundary conditions, ventilation, and equipment wear on the results are often overlooked. The fire growth model is the most commonly used and widely recognized model in fire assessment, both domestically and internationally. It accurately describes changes in heat release rates during a fire. When ignoring the errors in the ignition phase, the fire growth model can be represented as:

$$\dot{Q} = \alpha t^2 \tag{1}$$

where $\dot{Q}$ is the heat release rate of the fire source in kW; t is the time in units of s; and α is the fire growth coefficient in units of $\mathrm{kW/s^2}$.

The ignition point studied in this paper is inside a room on the first floor of the building, with the fire source located at the center of the room. The high-speed fire growth coefficient is utilized due to the combustible materials primarily consisting of items such as books and shelves. According to the Chinese Technical Standard for Smoke Prevention and Exhaust Systems (GB51251-2017) [24], Table 3 shows that $\alpha = 0.04689\ \mathrm{kW/s^2}$. It is calculated that the time to reach the maximum heat release rate is 357 s. The simulation time is set to 600 s.

Table 3. Common fire growth factors.

Growth Type	A ($\mathrm{kW/s^2}$)	Typical Combustible Materials
superhigh speed	0.1878	Oil pool fire, flammable decorative home
high speed	0.04689	Wooden shelf pallets, foam
medium speed	0.01172	Cotton and polyester items, wooden offices
low speed	0.00293	Heavy wood products

2.5. Grid Settings

In numerical simulations, finer mesh divisions improve resolution accuracy in both spatial and temporal dimensions, enhancing result credibility. However, finer meshes require longer computation times, necessitating a balance between accuracy and speed to determine mesh size. According to the FDS User Guide [25], if the ratio between the characteristic diameter of the fire source D^* and the grid size δ is $4 \leq D^*/\delta \leq 16$, the grid division is generally appropriate. If $D^*/\delta > 16$, the grid division is relatively fine. Conversely, if $D^*/\delta < 4$, the grid may be too coarse. The calculation formula for the characteristic size of the fire source is as follows:

$$D^* = \left(\frac{\dot{Q}}{\rho_\infty C_\mathrm{p} T_\infty \sqrt{g}}\right)^{2/5} \tag{2}$$

$$\varphi = \frac{D^*}{\delta} \tag{3}$$

where $\dot{Q}$ is the heat release rate of the fire source (6 MW), C_p is the specific heat capacity of ambient air (1.005 J/(kg·K)), ρ_∞ is the air density at standard atmospheric pressure (1.2 $\mathrm{kg/m^3}$), T_∞ is the ambient temperature (20 °C), and g is the acceleration due to gravity

(9.8 m/s^2). Using a 0.12 m × 0.12 m × 0.12 m grid, the calculated D^* at a heat release rate of 6 MW is 16.36, which is within a reasonable range. Therefore, this grid size can meet the simulation accuracy requirements of this study.

2.6. Grid Independence Verification

The number of simulation grids impacts both the accuracy and duration of the simulation. To expedite results, the main measurement area was set to a grid size of 0.12 m × 0.12 m × 0.12 m. Wider grids were used in other areas to reduce simulation time. Simulations were validated for grid sizes of 0.2 m × 0.2 m × 0.2 m, 0.3 m × 0.3 m × 0.3 m, 0.4 m × 0.4 m × 0.4 m, and 0.5 m × 0.5 m × 0.5 m. As shown in Figure 5, the simulation results for the 0.2 m × 0.2 m × 0.2 m, 0.3 m × 0.3 m × 0.3 m, and 0.4 m × 0.4 m × 0.4 m grids are similar. The results for the 0.5 m × 0.5 m × 0.5 m grid differed significantly from the other three grids. To achieve faster simulation speeds, a grid size of 0.4 m × 0.4 m × 0.4 m was selected for other areas.

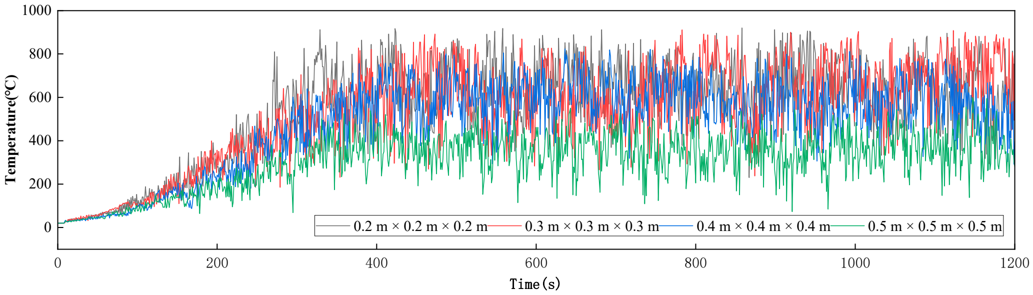


Figure 5. Grid Independence Verification Results.

3. Results and Discussion

3.1. Effect of Wind Speed on Fire Spread

The window partition walls are vital in fire protection design for building facades. When lateral external wind acts, flames and smoke spread downstream. Passing through the window partition wall impacts its leeward side. Figure 6 displays simulation results for four scenarios: W_1, W_4, W_5, and W_6. The figure illustrates that with increasing wind speed, flames and smoke gradually shift sideways from vertical upward propagation, with the angle of deviation increasing accordingly. The findings suggest that under weak lateral wind forces, flames and smoke predominantly ascend due to thermal buoyancy. In contrast, with stronger lateral wind force, wind speed becomes the primary factor, leading to a transition in fire propagation from vertical to simultaneous vertical and horizontal spreading. This shows that in the actual case of fire, the effect of ambient wind will cause the flame and smoke from the window to spread horizontally and vertically on the building facade at the same time.

3.2. Effect of Window Partition Walls on Vertical Fire Spread

Figure 7 presents the temperature distribution cloud maps for simulation scenarios W_1, W_2, W_3, and W_4 under no-wind conditions. The window partition walls are set to widths of 0 m, 0.3 m, 0.6 m, and 0.9 m. The figure illustrates that when a fire occurs near the L-shaped corner of a high-rise building, the smoke movement near the corner is different from the scenario without window partition walls. The simulated temperature with window partition walls is higher than without them. Additionally, as the width of the window partition walls increases, the temperature above the window and the rate of temperature increases per unit time both rise.

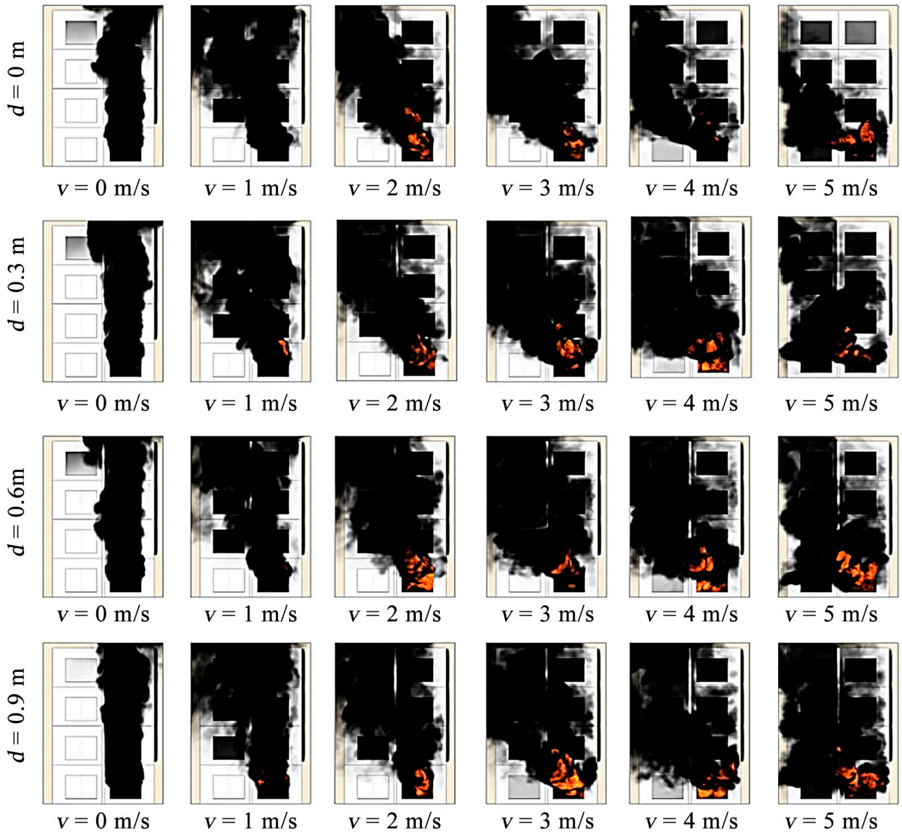


Figure 6. Smoke spread diagram.

Figure 8 depict the average temperature distribution of thermocouple Group D when the fire reaches a stable state after 357 s. As shown in Figure 8a, compared to the absence of window partition walls, it is evident that for every 0.3-m increase in the width of the window partition walls, the temperature near the L-shaped corner rises by approximately 100 °C. Figure 8b illustrates that the temperature of upper-level windows in the fire area increases as the width of the window partition walls expands. However, there is little difference in the temperature impact between a 0.3-m window partition wall and a no-window partition wall. The L-shaped structure formed by window partition walls results in faster temperature diffusion, consistent with the conclusion from Figure 6. Overall, the vertical fire protection effect of models with window partition walls is poorer compared to those without them.

Without window partition walls, the heat from the fire source quickly spreads to the open space. In contrast, a facade with window partition walls forms an L-shaped structure that obstructs the released heat, easily creating a chimney effect. This phenomenon aligns with the findings of Lu et al. [26], which state that "the width of the sidewall affects the height of the flame". As shown in Figure 9, window partition walls restrict the inflow of fresh air. To achieve thorough combustion, the flame draws in air, creating an upward induced airflow in the passage. The induced airflow has a certain velocity, so it can elongate the flame. Wider partition walls hinder air inflow more, resulting in a longer preheating zone and increased heat feedback. Thus, the chimney effect becomes more pronounced. It can be concluded that buildings with an L-shaped structure are more prone to vertical fire spread during a fire.

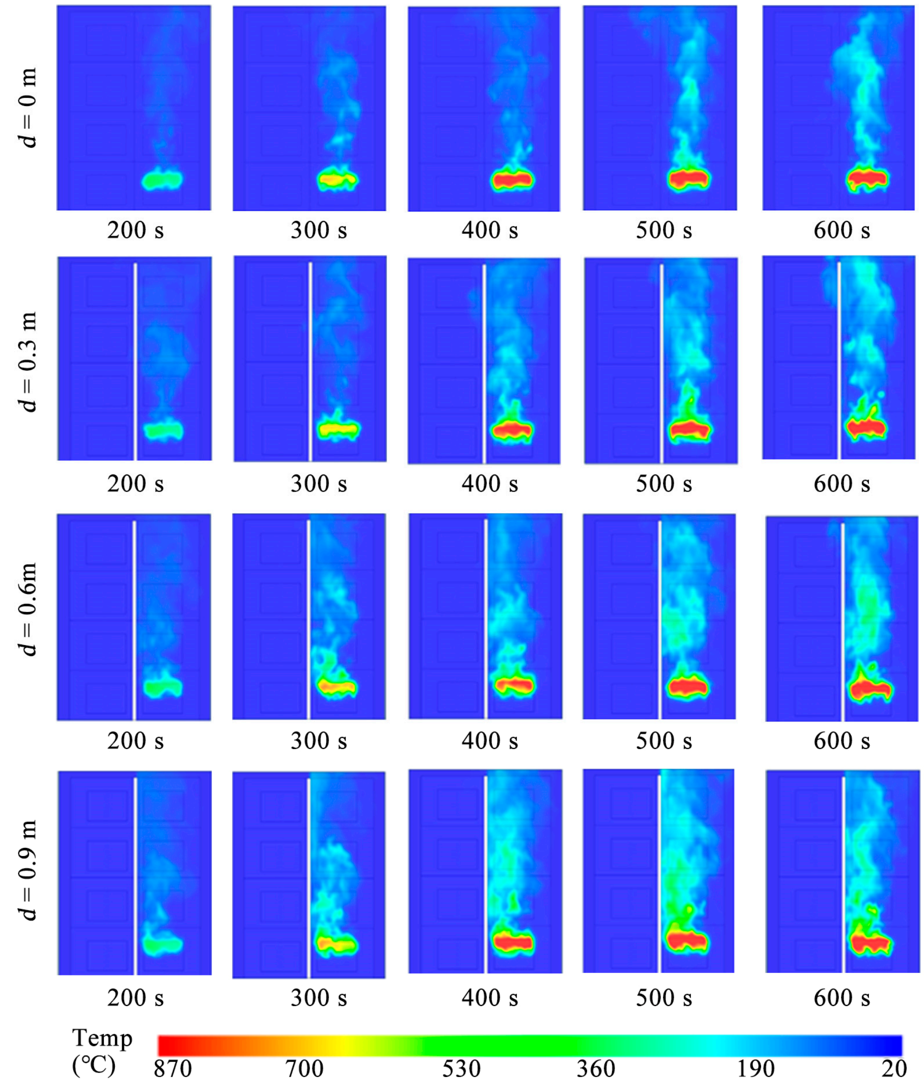
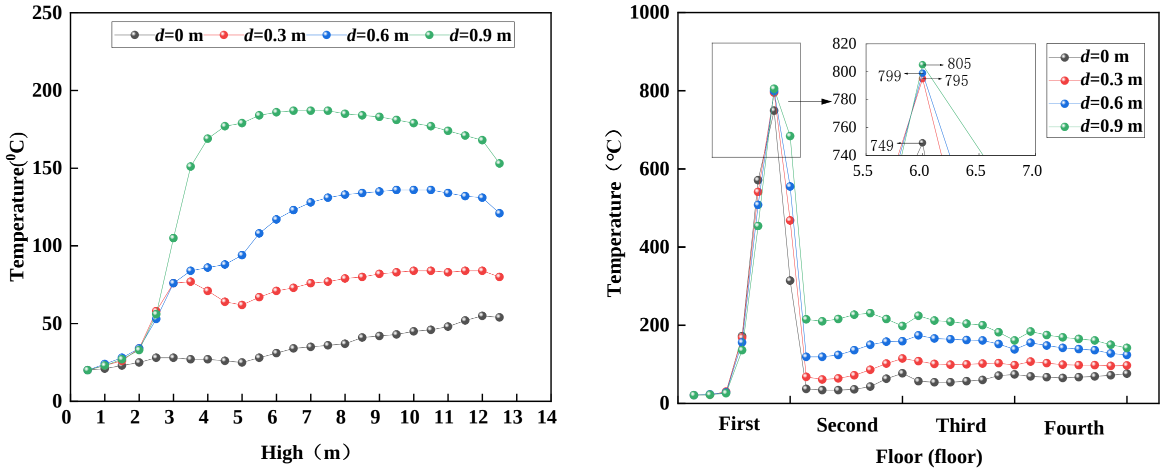


Figure 7. Temperature slice diagram.



(**a**)

(**b**)

Figure 8. Temperature profiles (**a**) Temperature distribution in wall corners (Group D); (**b**) Temperature distribution of rooms on the fire floor (Group C).

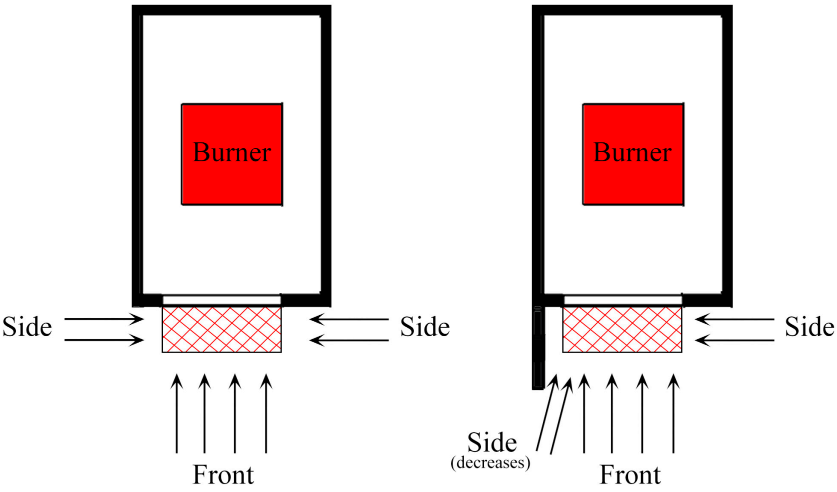


Figure 9. Entrainment model of ejected flame.

3.3. Effect of Window Partition Walls on Horizontal Fire Spread

Wind conditions were added to the four simulation experiments W_1, W_2, W_3, and W_4. Figure 10 illustrates the average temperature distribution recorded by group D thermocouples after the fire stabilized at 357 s. This control group study compares the fire-blocking effects of window partition wall widths of 0 m, 0.1 m, 0.2 m, and 0.3 m under wind speeds ranging from 0 to 5 m/s. The figure shows that the average temperature of the leeward-side windows decreases as the width of the window partition walls increases.

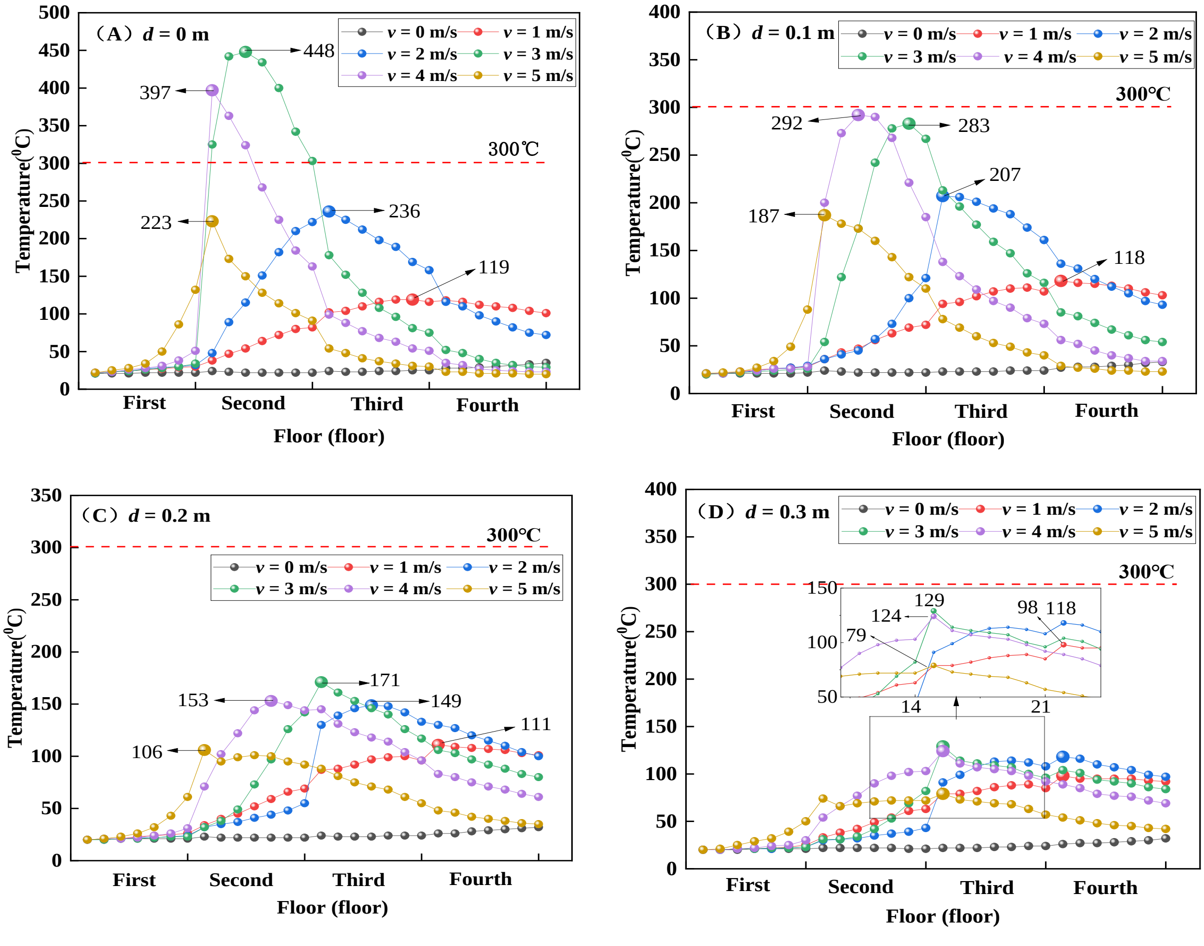


Figure 10. The average temperature distribution of leeward-side windows.

The critical temperature for glass breakage is set at 300 °C [27]. The width of the window partition walls is set to 0 m; at lateral wind speeds of 3 m/s and 4 m/s the leeward-side windows' glass surface reaches the critical temperature, with the highest temperature peaking at 448 °C. This is due to the absence of vertical barrier walls, which causes flame and smoke to deviate under the influence of ambient winds. Setting the width of the window partition walls to greater than or equal to 0.1 m results in a maximum glass surface temperature of 292 °C on the leeward-side windows, below the critical temperature, thus preventing glass breakage. The window partition wall can inhibit the horizontal spread of the fire.

Figure 11 illustrates the maximum temperature distribution recorded by group D thermocouples after the fire stabilized at 357 s.

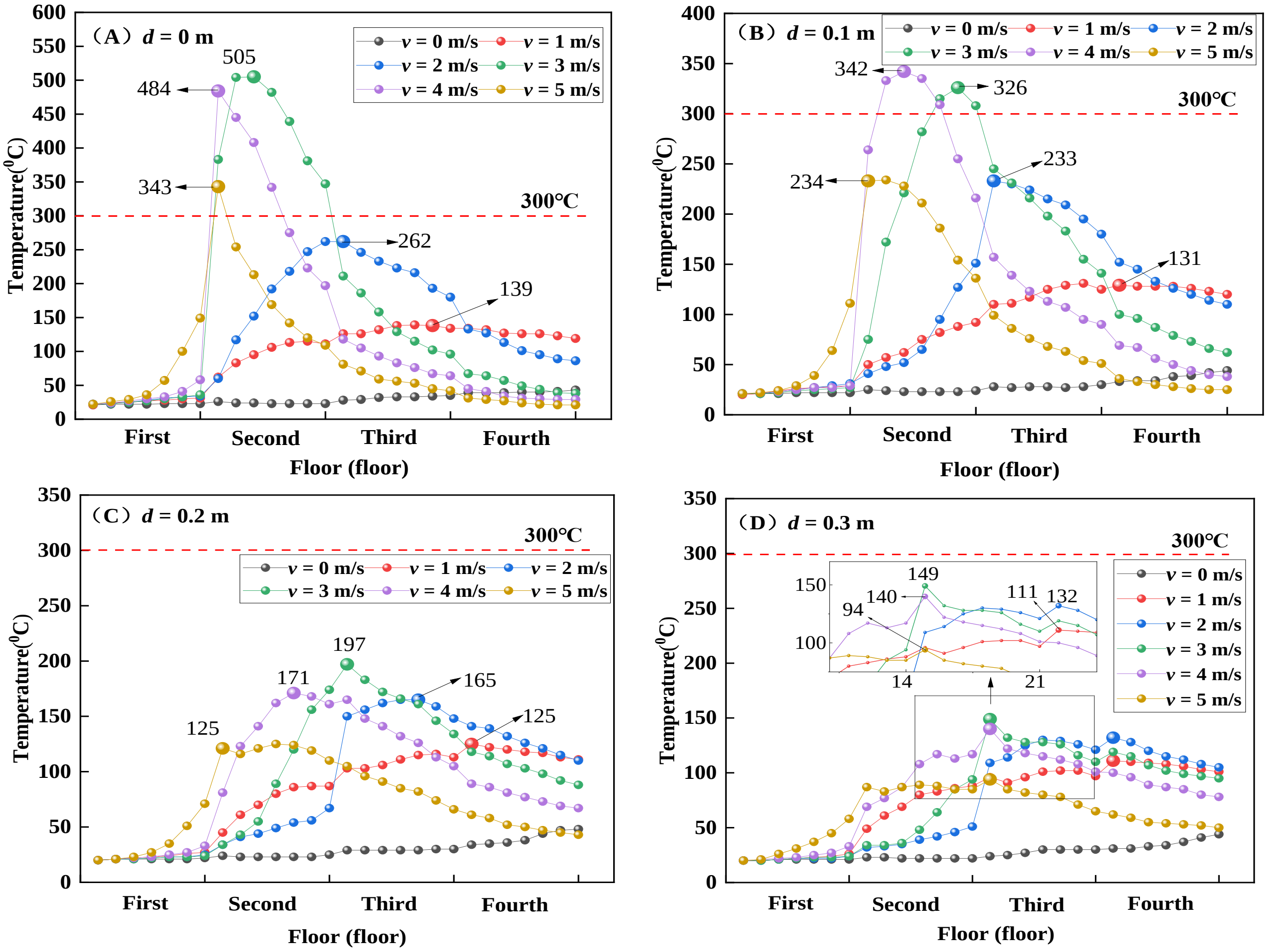


Figure 11. The highest temperature distribution of the leeward-side window.

When the width of the window partition walls is 0 m and the lateral wind speed exceeds 3 m/s, the glass surface of the leeward-side windows reaches the critical temperature, with the highest temperature peaking at 505 °C. When the width of the window partition walls is 0.1 m, the maximum glass surface temperature on the leeward-side windows is 342 °C, above the critical temperature, causing glass breakage. When the width of the window partition walls is greater than or equal to 0.2 m, the glass surface temperature on the leeward-side windows remains below the critical temperature.

3.4. Discussion

The study provides critical insights into the dual role of window partition walls in influencing fire spread behavior on building facades. Section 3.1 highlights that under weak lateral wind forces, flames and smoke predominantly ascend due to thermal buoyancy. However, stronger lateral wind forces lead to simultaneous vertical and horizontal spreading, showing that ambient wind significantly affects fire propagation. Such findings are critical in areas with significant wind activity, where well-designed partition walls can prevent horizontal fire spread, protecting adjacent buildings and higher floors.

Section 3.2 reveals that window partition walls facilitate vertical fire spread due to the chimney effect. As the width of the partition walls increases, the temperature above the windows and the rate of temperature increases per unit time also rise. In the L-shaped structure, the entrainment of air by the flame is impeded, resulting in a chimney effect, which enhances the propagation of the vertical flame. Hence, architects and engineers must balance the benefits of preventing horizontal fire spread with the risk of increased vertical propagation.

Section 3.3 demonstrates that the presence of window partition walls can inhibit the horizontal spread of fire under wind conditions. Wider partition walls effectively prevent glass breakage by maintaining lower temperatures on the leeward-side of windows. This is especially important in windy areas, where lateral winds can allow a fire to spread through the facade, increasing the risk for upper floors and adjacent areas. By incorporating these findings, fire safety engineers can perform more accurate fire risk assessments and implement preventive measures accordingly.

Overall, this study makes significant contributions to the field of fire safety engineering by addressing the geometric properties of window partition walls, an under-explored area in fire dynamics. The practical design insights provided can be directly applied in building design and retrofitting, offering clear guidelines on enhancing fire safety through architectural features. Furthermore, the research encourages the integration of advanced simulation tools like FDS into the fire safety design process, promoting the use of cutting-edge technology to predict and mitigate fire risks effectively. These findings lead to safer building designs, improved fire safety standards, and more effective fire risk management strategies in high-rise and urban environments. Future research should incorporate actual fire cases and experimental data to verify and refine these conclusions, providing more reliable fire protection design references, which can also contribute to the formulation of safe and reliable building fire codes.

4. Conclusions

This study, through numerical simulation, found that during a fire, the spread of flames on building facades can deviate due to thermal buoyancy and environmental wind. This deviation causes the fire to spread both horizontally and vertically. Based on this issue, this study examines how the width of window partition walls influences flame propagation on building facades under ambient wind conditions through numerical simulation methods. As a result, the following conclusions are drawn.

1. In high-rise building fires, the L-shaped structure created by window partition walls and walls limits the ingress of fresh air. The L-shaped structure causes the flame to draw in air, forming an upward induced airflow in the passage, thereby triggering the generation of the chimney effect. The results indicate that wider window partition walls impede air inflow more, resulting in a longer preheating zone and stronger heat feedback, thus intensifying the chimney effect.

2. After burning for 357 s, the fire stabilized. The presence of 0.1 m window partition walls inhibits the horizontal spread of building fires compared to no-window partition walls. However, at wind speeds of 3 m/s or 4 m/s, the window partition walls cannot fully prevent fire spread. With window partition walls measuring 0.2 m or 0.3 m in width, and under ambient wind speeds ranging from 0 to 5 m/s, they effectively hinder the horizontal propagation of building fires.

3. Window partition walls facilitate vertical fire spread while restricting horizontal fire spread. The promotion of vertical temperature by window partition walls is much less significant compared to their inhibition of horizontal temperature. The promotion of

vertical temperature by window partition walls becomes more evident with greater width. In this study, under ambient wind speeds of 0 to 5 m/s, 0.2 m can be considered as the critical width of window partition walls to inhibit the horizontal spread of building fires.

These conclusions are expected to serve as a basis for developing fire regulations and guiding architectural designers. In the future, it is hoped to couple multiple facade components for research on facade fires in high-rise buildings, providing more accurate data references for research in the field of high-rise building fires.

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