Research Article

Simulation Study on the Influence of Fire Partition on Curtain Wall Temperature in Super High-Rise Buildings in China

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Received 12 April 2021; Revised 12 May 2021; Accepted 4 June 2021; Published 1 July 2021

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The poor fire resistance characteristic of super high-rise curtain wall makes the curtain wall design one of the main approaches to improve its capacity for prevention and control over fire and smoke spread. The propagation of smoke leads to the increase in the temperature of the curtain wall on the upper and lower floors of the fire floor and consequently leads to glass fracture and other serious consequences. Current codes have control over fire resistance performance and size of fire partition materials but do not include requirements on the position of curtain walls on floors. By changing the position of fire partition in curtain walls, the paper carries out three comparative simulation experiments on two forms of fire partition: spandrel and fire prevention cornice. Besides, PyroSim is used to calculate the comparative simulation of fire and smoke spread and obtain the data on temperature variation nephogram and monitoring points in the center line of glass curtain walls during different fire scenarios, so as to discuss the influence of different positions of spandrels and fire canopy on fire hazard and smoke. This study finds out the following: fire canopy can better prevent the longitudinal spread of fire smoke than spandrels. The fire canopy above spandrels can reduce the flue-gas temperature. The higher the spandrels above floors, the faster the temperature of the central lines of glass curtain walls above fire floors reduced. However, the higher the spandrels above floors, the more uneven the distributions of high-temperature regions and low-temperature regions, thus leading to the increase in horizontal temperature differences of glass panels. This research conclusion can be taken as a reference for fire protection design of super high-rise glass curtain wall.

1. Introduction

1.1. Fire Characteristics of Glass Curtain Wall in Super High-Rise Buildings. Tempered glass is extensively used in the curtain wall in modern high-rise buildings [1]. Through the analysis of super high-rise building fire, vertical spread on exterior walls is an important form of fire spread in high-rise building [2]. There are more demanding requirements on design for fire protection in the use of glass curtain wall. Once the fire protection design is unreasonable, the fire risk index tends to rise [3]. In case of fire, the high temperature and immense heat of the flame will break or deform the curtain wall if the fire origin is close to the curtain wall. Temperature differences induce variations in air pressure indoor and outdoor, and the glass explodes, which lead the smoke still to roll up or down along the curtain wall. Oxygen, the outdoor combustion-supporting gas encourages the fire to spread further. Even if it meets the requirement of gap filling between curtain wall and major structure, fire and smoke spreading cannot be avoided due to unfavorable fire prevention of glass curtain walls.

1.2. Related Factors of Fire Resistance Performance of Glass Curtain Wall. Compared with other types of traditional construction materials, normal glass is fragile with limited tensile properties. The thermal properties have been extensively studied before [4]. As for the breaking temperature of fire resistance of glass panels, foreign scholars obtained different data through experiments. Kim and Taber specify the breaking temperature of glass directly exposed to flame radiation: 150–175°C for ordinary glass and 350°C for
tempered glass. Quaglia proposed that the temperature standard is 100°C for breaking ordinary glass and 270°C for tempered glass. But Frantzich used 300°C as the temperature standard for both types of glass [2]. Fire resistance experiments on glass panels of different thickness and layers were carried out in domestic and foreign research institutions with ambient temperature data obtained when the panel surface of various types facing the fire breaks. See Table 1 for the corresponding ambient temperature data when the panel facing the fire cracks obtained after various experiments performed with various types of glass in various research institutions. The disproportional scope of tests regarding the thermal and mechanical properties is related to complexity of test execution of the latter. This particularly applies for the properties of glass at elevated temperature. The degradation of stiffness and strength properties of glass is caused by accelerated corrosion that is present with rising temperature [6]. Studies proved experimentally that the tensile bending resistance of glass shows high sensitivity to temperature. Regarding the modulus of elasticity, its value decreases significantly for temperatures above 600°C and thus certainly represents an influencing parameter for design [7].

In recent years, except the forms glass panels and fire endurance discussed in research about the fire resistance of glass curtain wall, glass panel, temperature distribution of panels, and structural support are illustrated as well. Research indicates that as the size of tempered glass has a great influence on fire-resistance performance, it is necessary to limit the size of glass. And the vertical length impact is greater than the horizontal length. The breakage of tempered glass, which is wildly used in glass curtain, relates to the maldistribution of temperature. The temperature gradient generates temperature stress in glasses; once the stress is beyond the tolerance limit, cracks appear; then, the glass breaks. So, the value of temperature difference can work as criterion of glass breakage [8]. Besides, most of the thermal breakage description and its realistic prediction are known to be highly affected by the variability of material properties. Boundary conditions and compartment fire dynamics can also strongly modify the temperature distribution and evolution in glass, thus resulting in possible severe variations for the expected failure time [9–13].

1.3. Simulation Technology Is an Effective Means to Optimize the Existing Fire Protection Design Problems. Current codes mainly prevent the fire spreading vertically through outdoor ways by stipulating the setting of entity walls or fire canopy between the upper and lower floor openings and the setting of the combustion performance of exterior wall insulation and decorative materials [2]. Although the specific provisions for the size of the fire partition design were included in relevant national codes, the partition height and width required are only a minimum. See Table 2 for provisions on the design of glass curtain wall for super high-rise buildings in “Code of Design on Building Fire Protection and Prevention” (2018 Edition) [14].

In practical project application, Flame Rolling cannot be securely avoided with the fire code and fire-fighting facilities. How to select and set the partition still needs to be clearly understood through calculation and simulation. In this regard, several research studies have been dedicated over the last years to the development and/or assessment of specific design regulations and novel design concepts for structural glass systems, including extended experimental and finite element (FE) numerical investigations related to connections, composite assemblies, and hybrid systems [10]. In recent years, domestic and foreign scholars have tried to use different software simulations and numerical calculations to analyze the impact of fire partition on fire spread along glass curtain wall. The research indicates the following: FDS software can demonstrate experimental results with reasonable details. MVHS model can effectively forecast breakage within curtain walls and temperature distributions of space in a fire [15]. Through contrastive analysis of the impact of fire prevention cornice and spandrel on fire outside small houses. It concludes that fire prevention cornice is probably better in preventing fire, and at least 1.2 m of spandrel can be replaced by 60cm horizontal projection [16]. Furthermore, the size and shape of the window should be considered when the horizontal projection and spandrel walls are designed [17]. The previous predictive model for plume temperature proposed by Quintiere is popularized to the ejected flame above an eave by including the dimensions of the rectangular fire source, as well as the width of eave [17].

In this study, PyroSim was used to simulate the influence of different fire partitions for super high-rise glass curtain wall against fire and smoke propagation. The simulation process was divided into the following steps: (1) establishing geometric model; (2) setting the fire scene including fire origin location and fire load, simulation range and boundary conditions, fire resistance performance of the glass curtain wall, the monitoring point and the slice location to obtain data, grid density, and the simulation time; (3) calculating through FDS/smokeview for simulation calculation and postprocessing for the result. In this process, the fire and smoke temperature cloud pictures and the temperature change curve of the monitoring point for the required area in the model could be visualized in the simulation results through setting the model [18]. The main contributions of this paper are gaining the temperature value of central line in adjacent floor and glass panel by changing the position of fire partition, analyzing the vertical temperature variation curve of curtain wall and temperature distribution of glass panel, and discussing the possible negative factors of adjacent floor explosion, thereby choosing effective fire partition settings and fire-fighting devices.

2. Materials and Methods

2.1. Establishing the Abstract Model. Suppose that a fire broke out in an office of standard story in the high-rise zone in a super high-rise building with a height of 420 m, floor slab thickness (including the decorative finish) of 200 mm, and a glass curtain wall with a thickness of 6 mm as its architectural skin. The glass curtain wall of the fire origin
floor broke. The flame and high-temperature smoke consequently billowed from the vent. According to the requirements of national codes, fire partition in the form of a spandrel with a height no less than 1200 mm or a fire canopy with a width of no less than 1000 mm is needed for partition in the cross story section of the glass curtain walls. On the basis of meeting this requirement, six geometric models can be built through adjusting relative positions of the spandrel and the fire canopy to the curtain wall to find out the effects of the partition in different forms and positions on the fire spreading.

In the six geometric models, the spandrel of 1200 mm in height was adopted in models A, B, and C, while the fire canopy with a width of no less than 1000 mm is needed for partition in the cross story section of the glass curtain walls. On the basis of meeting this requirement, six geometric models can be built through adjusting relative positions of the spandrel and the fire canopy to the curtain wall to find out the effects of the partition in different forms and positions on the fire spreading.

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In model A, two non-combustible walls of 500 mm in height each were configured in the same plane immediately above and below the same floor structure as one spandrel. In model B, two non-combustible walls were configured in the same plane immediately above and below the floor structure with the one of 800 mm in height above and the one of 200 mm in height below as one spandrel. In model C, two non-combustible walls were configured in the same plane immediately above and below the floor structure with the one of 200 mm in height above and the one of 800 mm in height below as one spandrel. In model D, two non-combustible walls of 400 mm in height each were configured in the same plane immediately above and below the same floor structure as one spandrel. Additionally, a fire canopy of 1000 mm in width was configured in the middle of the wall. In model E, two non-combustible walls of 400 mm in height each were configured in the same plane immediately above and below the same floor structure as one spandrel. Additionally, a fire canopy of 1000 mm in width was configured on the top of the wall. In model F, two non-combustible walls of 400 mm in height each were configured in the same plane immediately above and below the same floor structure as one spandrel. Additionally, a fire canopy of 1000 mm in width was configured at the bottom of the wall (see Figure 1).

After the occurrence of a building fire, the flame and high-temperature smoke billowed from the vent on the curtain wall have a serious impact on the structure of the upper curtain wall in ushering the flame spreading upward. At the same time, the high temperature of the floor in fire may cause damage to the aluminum alloy frame and glass of the floors downward. As the falling high-temperature debris and flying sparks may have the combustibles in the room downstairs ignited, the fire spreading may well be leading downward [19]. In view of this, the scope of this simulation was set within the inner and outer area of the glass curtain wall of the fire floor and the other two floors immediately upstairs and downstairs in the super high-rise building. The law governing the temperature change in upper and lower glass curtain walls was investigated.

2.2. Design of Fire Scene

2.2.1. Material and Boundary. The main structures of the six models are wall and glass curtain wall. The thickness of the wall is 200 mm, and the material composition is concrete. The thickness of the glass curtain wall is 6 mm, and the material composition is calcium silicate. The specific components of the two materials are shown in Table 3.

2.2.2. Setting the Fire Load. Assuming that the fire occurred in an office floor of a super high-rise building, the $t^2$ model can be used to describe the development process of early fire in a specific space [20]. For the $t^2$ model, see equation (1) (NFPA204 (2002) [21]). With reference to “Office space with sprinkler failure” in “Technical specification for building smoke control” approved by the relevant department of Shanghai in 2006 [22] and fire categories of different functional buildings in NFPA204 (2002 Edition), a conservative setting of failure occurrence for both the common sprinkler system and Mechanical Smoke Exhaust System in office area, the fire grow rate is considered as faster-growing fire, and the fire growth coefficient $\alpha = 0.047$. Table 4 shows the fire growth coefficients $\alpha$ of the $t^2$ model and the maximum heat release rate and heat release time for different materials used in the design of different functional buildings [19].

$$Q = \alpha g t^2.$$ (1)

$Q$: heat release rate of fire (kW), $\alpha$: fire growth coefficient (kW/s²).

Without considering the influence of ambient wind, it is assumed that the ambient temperature is at 23°C. According

| Research structure | Glass panel | Thickness (mm) | Temperature (°C) |
|--------------------|-------------|---------------|-----------------|
| Manzello, a reputable fire research institute overseas [5] | Single-layer toughened glass | 6 | 400 |
| University of Science and Technology of China | Single-layer toughened glass | 6 | 350 |
| | Single-layer toughened glass | 10 | 470 |
| Tianjin Fire Research Institute of MPS | Double-layer toughened glass | 6 | 600 |
| Test result | Double-layer semitoughened laminated glass | 8 | 582 |

Table 1: Ambient temperature when the panel facing the fire cracks.

| Min height of a solid wall (m) | Min width of a fire canopy (m) |
|--------------------------------|--------------------------------|
| Automatic sprinkler — —        | 0.8 1.2                         | 1.0 |
to the calculation of $t^2$ for fire development, and in due consideration that Chinese fire fighters arrive at the fire site 5 minutes after receiving the fire alarm and get ready for dousing in 5 minutes, it is, therefore, assumed that fire fighters can carry out effective fire-fighting and control the development of fire 10 minutes after the fire [20]. According to the equation, the maximum heat release rate $Q$ is at around 16.9 kW, when firemen arrive. Considering the most unfavorable situation in the open office, due to the large office area, the fire origin is located in the middle of the fire floor 1 m away from the inner side of the glass curtain wall with the fire load set at 6 MW.

2.2.3. Configuring the Detecting Point and Section. In order to obtain the temperature characteristics of glass curtain walls on the upper and lower floors of the fire floor, monitoring points are set outside on the central line perpendicular and at equal distance to the curtain wall of each

| Table 3: The specific components of the two materials. |
|---------------------------------|----------------|----------------|
| Density                         | 2280.0 kg/m$^2$ | 720.0 kg/m$^2$ |
| Specific heat                   | 1.04 kJ/(kg·K)  | Custom         |
| Conductivity                    | 1.8 W/(m·K)     | 0.12 W/(m·K)   |
| Emissivity                      | 0.9             | 0.83           |
| Absorption coefficient          | 5.0E4 1/m       | 5.0E4 1/m      |

Figure 1: Profile of six types of fire partition of glass curtain wall.
floor within the simulation range. Thermal detectors are mounted at monitoring points with a horizontal distance of 10 mm to the curtain wall (see Figure 2). To obtain the temperature cloud pictures of the fire facing surface of the curtain wall, the temperature detection slice can be set at the fire facing surface of the glass curtain wall within the simulation range.

2.2.4. Generating the Grid. A reference to the relevant data suggests that the size of the fire characteristic diameter $D$ is the main concern in setting the grid size (20–26). In the process of fire simulation, when the grid size $d = 0.1D$ is selected, the fire simulation results can be infinitely close to the experimental results. The fire characteristic diameter $D$ is expressed in

$$D = \left( \frac{Q}{\rho c_p T \sqrt{g}} \right)^{2/5}.$$  \hspace{1cm} (2)

$D$: base diameter of the fire, $m$; $Q$: total heat release rate, kW; $\rho$: ambient air density, kg·m$^{-3}$; $c_p$: specific heat, J·kg$^{-1}$·K$^{-1}$; $g$: acceleration of gravity, m·s$^{-2}$.

According to the calculation of heat release rate at 1 MW, the characteristic dimension $D$ of the fire is 3.53 M. The grid size of about 0.4 m, therefore, meets the simulation requirements.

3. Results and Discussion

The scope of simulation covered real fire scenes of six models. In the process of fire, the basic logic for smoke control was as follows: in models A–F, the burner started ignition from 0 second. As a result, the glass panel nearest to the burner disappeared indicating that it had burst, and the sprinkler system failed. Control the HRR curve to keep it constant at around 6000 kW. At this time, the fire remains alive, but no longer continues growing. Slicing devices were set outside the glass curtain wall of each model to collect fragments of fire texture. Thermocouples were evenly configured on glass panels of upper and lower floors for data acquisition to observe the texture of fire smoke spread and the influence of smoke temperature on glass panels of the upper and lower floors. The period for simulation was 1200 s. The scene of fire smoke spread is shown in Figure 3.

3.1. Analysis of Fire Temperature Texture. The temperature cloud pictures for smoke distribution outside the curtain wall were intercepted every 100 s to observe the pattern governing the temperature change in smoke for each model. The simulation results are shown in Figures 4 and 5.

In fire Scenes A, B, and C, with the assumption that the height of the fire floor with $z = 0$ m, a clear temperature partition line appeared at the lower part of the spandrel with $z = 12$ m, between the fire floor and the immediate upper floor above. After a certain period, high temperature smoke cloud gradually appeared in the area above with $z = 4$ m. The area below with $z = 12$ m was almost kept below 25°C. It can be understood that, after the glass curtain wall of the fire floor burst, there was massive smoke gathering at the lower
part of the spandrel of the immediate upper floor during smoke spreading upward along the spandrel and glass panels above. In this process, a uniform high temperature zone came into being at the bottom of the spandrel. With the passage of time, the glass panels on the two adjacent floors above the fire floor have been heating up continuously from bottom to top at a pace for temperature rise far greater than those of the glass panels of two adjacent floors below the fire floor. During the process of temperature rising, changes in temperature of the smoke cloud were not yet evenly distributed on the whole glass panel, but rather affected by the fire load position. Along the center line of the glass panel,
|       | Scene A       | Scene B       | Scene C       |
|-------|---------------|---------------|---------------|
| 80s   | Slice Temp °C | Slice Temp °C | Slice Temp °C |
|       | 191           | 174           | 183           |
|       | 176           | 174           | 167           |
|       | 159           | 157           | 150           |
|       | 141           | 140           | 134           |
|       | 124           | 122           | 118           |
|       | 106           | 105           | 101           |
|       | 89.1          | 88.2          | 84.9          |
|       | 71.7          | 71.1          | 68.6          |
|       | 54.3          | 53.9          | 52.2          |
|       | 37.0          | 36.8          | 35.8          |
|       | 19.6          | 19.7          | 19.5          |
| 100s  | Slice Temp °C | Slice Temp °C | Slice Temp °C |
|       | 191           | 174           | 183           |
|       | 176           | 174           | 167           |
|       | 159           | 157           | 150           |
|       | 141           | 140           | 134           |
|       | 124           | 122           | 118           |
|       | 106           | 105           | 101           |
|       | 89.1          | 88.2          | 84.9          |
|       | 71.7          | 71.1          | 68.6          |
|       | 54.3          | 53.9          | 52.2          |
|       | 37.0          | 36.8          | 35.8          |
|       | 19.6          | 19.7          | 19.5          |
| 230s  | Slice Temp °C | Slice Temp °C | Slice Temp °C |
|       | 191           | 174           | 183           |
|       | 176           | 174           | 167           |
|       | 159           | 157           | 150           |
|       | 141           | 140           | 134           |
|       | 124           | 122           | 118           |
|       | 106           | 105           | 101           |
|       | 89.1          | 88.2          | 84.9          |
|       | 71.7          | 71.1          | 68.6          |
|       | 54.3          | 53.9          | 52.2          |
|       | 37.0          | 36.8          | 35.8          |
|       | 19.6          | 19.7          | 19.5          |

Figure 4: Continued.
there appeared an area big at the bottom and small at the top, forming a triangle with clear boundary, the area on the glass for temperature rising.

Comparing and analyzing the three fire scenes revealed that the fire development characteristics exhibited in Scenes A, B, and C were almost the same. That is, at 80 s, there was a more obvious temperature difference on the upper part of the fire layer at a temperature difference of 20°C roughly. At 100 s, a relative stable triangle heating area with clear boundary and relatively stable range took shape in glass panels of the upper two floors above the fire floor with a temperature difference of 40°C. After that, the temperature in the triangle area rose together. At about 230 s, the temperature in the triangle area exceeded 100°C with a temperature difference over 70°C compared with that of the external area. At about 300 s, high temperature spots reaching 150°C were detected in the lower part of the triangle area, i.e., the bottom of the spandrel above the fire floor. These high temperature spots detected continuous temperature rising and thermal diffusing. As a result, several flakes of high temperature zones came into being at around 420°C. These high temperature zones reached the top temperature and were mainly distributed on the glass panel on upper floors above the fire floor with the maximum temperature difference from that of the glass panel beyond the triangle. Since then, the fire was no longer growing in scale.

In the 230 s starting from the ignition, the temperature cloud pictures of Scene A and Scene B were almost the same. In contrast, the overall temperature of Scene C was about 10°C lower than that of the other two. In 300 s, there appeared four weak spots of high temperature evenly distributed in Scene A and Scene C. In parallel, two large flakes of high temperature flakes appeared in Scene B. After that, the fire continued growing in all three Scenes with the most uneven distribution of high temperature flakes in the largest area with the tendency to be spreading to three upper floors above the fire floor in Scene B. In contrast, the high

| Scene | Slice Temp °C | Slice Temp °C | Slice Temp °C |
|-------|---------------|---------------|---------------|
| 300s  | 191           | 174           | 183           |
| 420s  | 193           | 176           | 183           |

(b) Figure 4: Smoke temperature cloud pictures of fire Scenes A, B, and C.
Figure 5: Continued.
temperaturespotsinSceneCwerenotcompletelyemerging
together into a whole flake. Although they were scattered in a
larger area, they were still scattered within the high tem-
perature area. In high temperature flake distribution, Scene
A was in the medium. When the fire in three fire scenes
reached the maximum scale, the highest temperature of
Scenes A and B exceeded 190°C. The highest temperature of
Scene C is only 180°C.

In fire Scenes D, E, and F, after cracking in the glass panel
of the fire floor, the smoke spread upward. In the early stage
of the fire, the fire canopy between the fire floor and its upper
floor blocked most of the smoke. Consequently, the tem-
perature of the smoke under the fire canopy increased
rapidly. With the growth of the fire in scale, part of the
smoke continued spreading to upper floors. Similar to that of
the three Scenes in the first series, the part of the smoke with
the most temperature rise was mainly aggregated in the
upper curtain wall of the fire floor. In contrast, the part with
the least temperature rise was in the lower part of the curtain
wall, which can be largely ignored. Different from the three
Scenes in the first series, distribution of the high temperature
zone in the cloud pictures of Scenes D, E, and F was not
featuring a temperature decreasing from bottom to top. High temperature distribution in Scenes D, E, and F featured
a floor-based pattern with high temperature smoke aggre-
gated on the top of the floor below the fire canopy. Con-
sequently, the temperature rise of the smoke in the floor was
more evenly distributed without forming a high temperature
zone with a stable shape and a clear boundary. Much dif-
ference was exhibited in the temperature distribution on the
fire floor, the immediate upper floor, and the immediate
upper floor but one.

A contrastive study of the three scenes revealed that the
temperature distributions in the incubation stage of fire
growing were relatively similar. At about 150 s, the high
temperature zone of Scenes A, B, and C was distributed
under the fire canopy on the upper part of the fire floor with
temperature at 80°C, 85°C, and 90°C, respectively. The
temperature of the upper part of the curtain wall on the fire
floor began rising. The immediate upper floor saw a tem-
perature rise to around 50°C in Scenes A and B. Additionally,
no significant rise in temperature of the immediate upper
floor but one was detected in Scenes A and B. In contrast, a
significant rise overall in temperature of the two immediate
upper floors above the fire floor was detected in Scene C. At
around 200 s, the high temperature zones of Scenes A, B, and
C were still densely congregated under the fire canopy on the
upper part of the fire floor at 150°C. However, temperature
distribution in curtain wall on upper floors made a differ-
ence. Temperature of the curtain wall on the immediate
upper floor reached 60°C. Additionally, the temperature in
some parts of the curtain wall on the immediate upper floor
but one exceeded 40°C in Scene A. In Scene B, the tem-
perature of the curtain wall on the immediate upper floor
reached 70°C. No appreciable temperature rise was detected
in the curtain wall on the immediate upper floor but one. In
contrast, the temperatures of the curtain wall on the im-
mediate upper floor and the immediate upper floor but one
were almost the same at 50°C. At around 300 s, the high
temperature zones of Scenes A, B, and C were still densely
aggregated under the fire canopy on the upper part of the fire
floor at 230°C, 200°C, and 240°C, respectively. In Scene A, the
high temperature zone on the curtain wall of the immediate
upper floor was distributed below the fire canopy on the
upper part of the immediate upper floor at 140°C. In con-
trast, the temperature of other parts of the curtain wall was at
around 90°C. The temperature of the curtain wall on the
immediate floor but one, in some parts, rose to around 60°C.
In Scene B, the high temperature zone on the curtain wall on
the immediate upper floor was distributed below the fire
canopy on the upper part at 100°C. In contrast, the tem-
perature of most areas of the curtain wall was at around
80°C. There was no appreciable rise in the temperature of the
curtain wall on the immediate upper floor but one. In Scene

![Figure 5: Smoke temperature cloud pictures of fire Scenes D, E, and F.](image)
Complexity 11

Figure 6: Thermal characteristics changing with time detected from monitoring points (Scenes A, B, and C).
C, the high temperature zone on the curtain wall on the immediate upper floor was distributed below the fire canopy on the upper part at around 85°C with uneven thermal distribution. In addition, the temperature in some parts of the curtain wall on the immediate upper floor but one rose to around 65°C. At around 400 s, the fire reached its maximum in scale with the fire growing law remaining the same. In Scene A, the high temperature zone on the curtain wall on the immediate upper floor was expanded to almost the entire curtain wall at 140°C. The temperature of the curtain wall, in parts, on the immediate upper floor but one exceeded 70°C. In Scene B, the high temperature zone on the curtain wall on the immediate upper floor was expanded to almost the entire curtain wall at 90°C with no appreciable rise being detected in the temperature of the curtain wall on the immediate upper floor but one. In scene C, the high temperature zones on the curtain wall on the immediate upper floor were densely aggregated in the middle of the curtain wall over 90°C. Uneven thermal distribution was detected in the curtain wall on the immediate upper floor but one at a peak temperature of 90°C boasting a clear temperature difference of 50°C.

3.2. Analysis of Glass Panel Temperature Monitoring Points in Fire. According to the analysis above, after the curtain wall of the fire floor was cracked, the temperature change in the curtain wall of two immediate upper floors was larger than that of the other two immediate lower floors. According to the location of the fire load, monitoring points were set outside on the central line perpendicular to and at equal distance to the curtain wall on the two immediate upper floors (see Figure 2) in various scenes to observe the changes with the time (see Figures 6 and 7) and the space (see Figures 8 and 9).

In the fire Scenes A ~ C, with the spandrel as the fire partition, Figure 6 shows the law for temperature change in the glass curtain wall with time, and an overall similar trend of development of the three fire scenes; that is, starting from the detection point at the bottom of the glass curtain wall on the immediate upper floor, the temperature of the smoke gradually decreases from bottom to top at the pace of temperature decreases at about 10°C ~ 20°C/1.5 m. However, in the specific data in Figure 7, when the fire scale reached the maximum, the fire in Scenes B and C had different effects on the temperature of curtain wall on the immediate upper floor, respectively. Among monitoring points THCP24, THCP25, and THCP26 outside the curtain wall on the immediate upper floor, the lowest temperature was detected in Scene B, the highest temperature in Scene C, and the medium temperature in Scene A. Among monitoring points THCP27, THCP28, and THCP29 outside the curtain wall on the immediate upper floor but one, the data was almost the same for Scenes A and C. The highest temperature was detected in Scene B. This was especially true for data acquired from monitoring points THCP28 and THCP29 with temperature 10°C higher than that of the other two sites.

In Scenes D ~ F, with the fire canopy as the fire partition, as the monitoring point THCP29 was configured above the fire canopy in Scene F, no temperature data of the two immediate upper floors above the fire floor can be acquired from it. Consequently, contrastive data analysis was not available. Figure 8 shows the temperature change of glass curtain wall with time. The overall trend of the three Scenes was as follows: the temperature of the curtain wall on the immediate upper floor was significantly higher than that of the curtain wall on the immediate floor but one, with a temperature difference of 30°C ~ 40°C. The temperature of glass curtain wall on each floor increased gradually with the increase in height, which was obviously different from that of characteristics in Scenes A–C. In the specific data in Figure 9, when the fire scale reached the maximum, the values of THCP24, THCP25, and THCP26 at the three monitoring points on the immediate upper floor in the three Scenes were almost the same. The only difference of the temperature at the top of the curtain wall in scene E was slightly higher. In scene F, temperature at the bottom of the curtain wall was slightly higher within a difference within 5°C. In the smoke temperature characteristics for curtain wall on the immediate upper floor but one, remarkable changes were detected at the three scenes. The overall temperature of curtain wall in Scene E was lower than that of the other two. In contrast, the temperature of curtain wall in Scene F was the highest in a relative stable range of
Figure 8: Thermal characteristics from monitoring points changing with time (Scenes A, B, and C).
57°C~65°C. In addition, the temperature of curtain wall in Scene D followed up in a relative stable range of 28°C~55°C. In contrast, all temperature data of curtain wall acquired in Scene E were among the lowest, below 40°C, without obvious inflection on the characteristics.

4. Conclusions

4.1. The Fire Canopy Is More Effective than the Spandrel in Blocking the Longitudinal Spreading of Fire and Smoke. From the comparative and contrastive study of the simulation in the six fire Scenes A ~ F, it was clear that all external curtain walls on all upper floors above the fire floor were affected by the fire smoke spread as can be seen from the change in temperature. However, the contrastive study over the two series of fire Scenes A ~ C and Scenes D ~ F further revealed that, within the range allowable in the Code, the effect of the spandrel as the fire partition on the longitudinal spread of fire smoke was significantly lower than that of the fire canopy. In Scenes A ~ C, the curtain wall saw a gradual decrease in the temperature from bottom to top bearing no significant relations to the number of floors. In contrast, the curtain wall saw a decrease in the temperature of curtain wall from bottom to top by floors bearing significant relations with the number of floors at a decrease rate far greater than those of Scenes A ~ C. It can be seen that there are more obvious advantages in the application of the fire canopy as the vertical separation for smoke spreading along the curtain wall than that of the spandrel. This especially holds true for blocking the smoke spread between floors, and controlling the smoke temperature in the fire floor and its adjacent floors. However, compared with the spandrel, the structure of fire canopy has more significant impacts on the façade of super high-rise buildings, in the façade and fire protection design. Therefore, it still needs to be balanced according to the actual situation.

4.2. Configuration of the Fire Canopy on the Upper Part of the Spandrel Is More Conducive in Reducing the Smoke Temperature along the Curtain Wall. Through comparing data from Scene D, Scenario E, and Scene F, the relationship of curtain wall temperature to the position of the fire canopy can be understood as follows: the fire canopy configured on the upper part of the spandrel can secure the lowest temperature of the curtain wall on upper floors over the fire floor. Similarly, the fire canopy configured in the middle of the spandrel can facilitate a medium temperature of the curtain wall on upper floors over the fire floor. The fire canopy configured in the bottom of the spandrel can lead to the highest temperature of the curtain wall on upper floors over the fire floor. In other words, the higher the fire canopy is configured on the spandrel, the more effective it is to block the spreading of smoke and rising of temperature. Therefore, when the fire canopy is configured as the fire partition in the building façade design, it is suggested that the fire canopy be set on the upper most part of the spandrel of each floor. This configuration is more effective to reduce the smoke spreading between the partitioned floors and providing versatility in a continuous design for the glass curtain wall on each floor.

4.3. Different Configuration of the Spandrel Has Different Effects on the Horizontal and Vertical Spreading of Smoke. From a comparison study of Scenes A, B, and C, and the vertical distribution of temperature along the glass curtain wall, it can be concluded that, under the premise of meeting the requirements in the code and standard, the higher the spandrel configured in relation to the floor, the lower the temperature along the central line of the glass curtain wall on upper floors above the fire floor. On the one hand, the higher the spandrel configured, the more the aggregation in the distribution of high temperature zones in the center of glass curtain wall on upper floors over the fire floor. Meanwhile, the distribution of high temperature zones and low temperature zones becomes increasingly uneven with greater difference in temperature. That is, in relative position to the floor, the higher the spandrel is configured, the more it is unfavorable to the horizontal spreading of the smoke. To sum up, the configuration of spandrel should not only meet the minimum requirement on height of 1200 mm as specified in the fire protection code. Moreover, the position relative to the height of the floor also has a significant impact on the temperature value and temperature distribution of the glass curtain wall on upper floors. There is a clearly different correlation between the height of the spandrel relative to the floor and the temperature value and distribution of the glass curtain wall on upper floors. Therefore, in the actual curtain wall design, it is necessary to determine the specific height of the position through simulation requirements so as to ensure a comprehensive optimal solution to hinder the vertical and horizontal spread of the smoke and temperature.
4.4. The Configuration of Fire Partition Shall Be Included into the Design of Fire-Fighting Facilities. According to the smoke temperature cloud pictures through simulation, obvious difference could be found out between the textures of the temperature cloud pictures with the spandrel as the fire partition and the temperature cloud pictures with the fire canopy as the fire partition for the curtain wall. The temperature cloud pictures for the former exhibited an aggregation of the high temperature zones to the central line of the curtain wall forming a high temperature zone with obviously clear edges. In parallel, the temperature cloud pictures of the latter presented a gradual diffusion of high temperature zones to the entire curtain wall with time in even thermal distribution. There was no obvious aggregation at different temperatures, and no high temperature zones with clear edges were formed. To prevent the curtain wall from cracking, it is necessary to pay attention to the temperature of the area with the minimum thickness on the entire curtain wall. Therefore, in the configuration for fire protection, simply increasing the overall cooling capability is inferior to adopting a flexible cooling method according to the actual temperature distribution. Linkage operation for thermal sensors in all monitoring points of each layer of glass panel is suggested. In the early stage of fire growing, a well-targeted centralized cooling in high temperature area is more operational effective with less resource consumption than overall cooling.

Based on existing rules and regulations, this study utilizes PyroSim software to simulate fire scenarios in super high-rise buildings with different fire partition designs. Advantages and disadvantages are decided according to the temperature value changes and distributions of glass curtain walls, so as to optimize fire partition designs. In this process, relevant parameter settings, such as the materials and boundaries of fire scenarios, are excessively complicated. Due to different varieties, the glass panel specifications and structures of the curtain wall in super high-rise buildings are different. When a fire occurs, the smoke spread is easily influenced by the wind environment. These factors induce uncertainty when it comes to the setting of boundary conditions by software simulation, thus making it difficult to control the results of simulation. The finite element simulation can simplify the above-mentioned parameters. However, if the parameters are explicit in subsequent simulations, the conclusions will become closer to practical scenarios.

In summary, there are many possibilities to PyroSim to actual scenarios, and the corresponding problems will be encountered. In future work, we will further compare the feasibility of these above strategies.

Data Availability

All the data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

Acknowledgments

This work was supported by Optimization Design for Vertical Penetrating Space of High-Rise Based on Performance Fire-Protection-A Case of the Guangdong-Hong Kong-Macau Great Bay Area, National Natural Science Foundation of China (51908357), 2020.01-2022.12, and Research on Vertical Through Space Optimization Design of Super High-Rise Buildings Based on PyroSim Software Simulation, Shenzhen University (000002110332), 2019.09-2022.09.

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