

Experimental and Numerical Study of Fire Spread upon Double-skin Glass Facades

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Abstract: This paper presents experimental and numerical studies of fire and smoke movement in the cavity of double-skin glass facades. The experimental tests were conducted using a two-storey rig with double-skin facade installed. Test results showed that double-layer of toughened glass panes broke when the temperatures reached about 600°C–800°C; the fire and smoke plume from the fire room were more likely to impede on the external skin in the cavity at the steady burning stage, and this could cause the external skin to break. The FDS model was employed to simulate one of the experimental tests and further used to study the effect of fire sources and cavity depths. Numerical modellings show good agreement when comparing the modelled temperatures with the measured temperatures next to the internal skins and external skins. For fully-developed fires in the modelling scenarios, the fire and smoke plume hit the external panes without any attaching to the internal panes. The fire and smoke plume could break the external skin but the internal skins are safe at low temperatures.

Key words: glass facade, double-skin facade, experimental study, numerical modelling, FDS

INTRODUCTION

In recent years, glass facades have gained more and more popularity in developing areas due to its characteristics such as durability, better appearance, and indoor environment with daylight. However, glass facades bring challenges to building fire safety due to the extensive use of highly breakable glass and deformable metal materials at high temperatures. Fire and smoke can spread to upper floors through broken openings on the system. Fire and hot gases can also spread vertically

through the perimeter gap between floor slabs and curtain walls, if the perimeter is not sealed properly or is damaged in fire. For double-skin glass facades, there is an additional risk of stack effect in the air cavity that may accelerate the fire and smoke spread to upper floors.

When glass is exposed to fire and smoke, temperature differences will increase between the heated glass area and the edge area. As a result, thermal stresses develop increasingly due to temperature differences, and the glass pane will break and even fall out at a certain level. Experimental tests have been carried out to study glass breakage in fires using room calorimeters and bench-scale test facilities^[1-6]. Gas and surface temperatures and heat fluxes for breaking glass were studied for numerous types of glass. Experimental results suggest that 3 mm thick float glass break out at about 360°C^[7] and 4-6 mm thick float glass fall out at about 450°C^[2]. Toughened glass (or tempered glass) appears to survive higher temperatures than float glass, and it is unlikely to break out until after the room fire has reached flashover (at about 600°C)^[4]. Double-layer of glass can withstand much more severe fires than single-layer glass. The Loss Prevention Council (LPC) studied double-glazed windows exposed to room fires and found that double-glazed windows using 6 mm thick floating glass would fail at about 600°C^[8]. Recent experiments show that double-layer toughened glass break out at a temperature of about 600°C–800°C^[9].

History fires and research reviews suggested that our knowledge of the behaviour of glass facades under fires is still limited^[10, 11]. Yet some experimental tests have been conducted to study the vertical fire spread on glass facade from the fire room to above floors using full scale test rigs^[12, 13]. The test results show that the progressive upward spread of fire from floor to floor is highly possible upon glass curtain wall if the building is not protected with sprinklers. However, it is necessary to study the mechanism of hot flame and smoke projecting out fire room through broken glass acting upon above glass panes.

The performance of double-skin facade in fire has attracted research interests in recent years, as well as fire and smoke spread in the air cavity. In Hong Kong, researchers conducted burn tests for double-skin glass facades using a medium-sized

facility^[14, 15]. More recently, researchers from Tianjin Fire Research Institute (TFRI) carried out experimental tests using a two-storey test facility^[9]. These experimental efforts provided necessary knowledge of the behaviour of double-skin glass facades under fires. The flame and smoke movement in the cavity is a very important issue since the stack effect in the cavity is a big concern of its safety. The contribution factors, like cavity depth, HRR, height of the test rig etc., play important role in the performance of double-skin glass facade under fires. More researches are needed to understand the fire safety of double-skin facade systems with different features.

This paper presents experimental and numerical studies of fire and smoke movement in the cavity of double-skin facades. The experimental tests early carried out at TFRI are presented. The FDS model is adopted to simulate one of the experimental tests and comparisons are carried out. The FDS model is further used to study fire and smoke movement in the cavity by taking into account different fire scenarios.

EXPERIMENTAL TESTS

A series of experimental tests were carried out at TFRI to study the breakage of double-glazed windows using toughened glass, and double-skin glass facades exposed to room fires as well as fire and smoke spread in the cavity. This paper introduces the three fire tests of double-skin glass facades conducted using a two-storey test rig. The experimental work has been published and more information is available in the literature^[9].

Test Rig

The test rig was built to simulate hotel rooms with the double-skin facade installed, shown in Figure 1. The lower and upper rooms had dimensions of 4×9 ×3.3m³ (high). The cavity depth between the inner and external skin was 860 mm.



Figure 1 Two-storey test rig.

Figure 2(a) shows the setup of the rooms and the internal skin of the facade. On the first floor, four panels of double glazing were installed. On the second floor, eight panels of double glazing were installed. Areas elsewhere on the internal skin were installed using plasterboards. Figure 2(b) shows the external skin of the facade. There were 12 glazing panels installed for the external skin. Table 1 summarizes the glazing details of the internal skin and external skin of the facade.

Thermocouples were used to measure local temperatures on the surfaces of glass panes. The thermocouple locations are shown in Figure 2 for both internal and external skins.

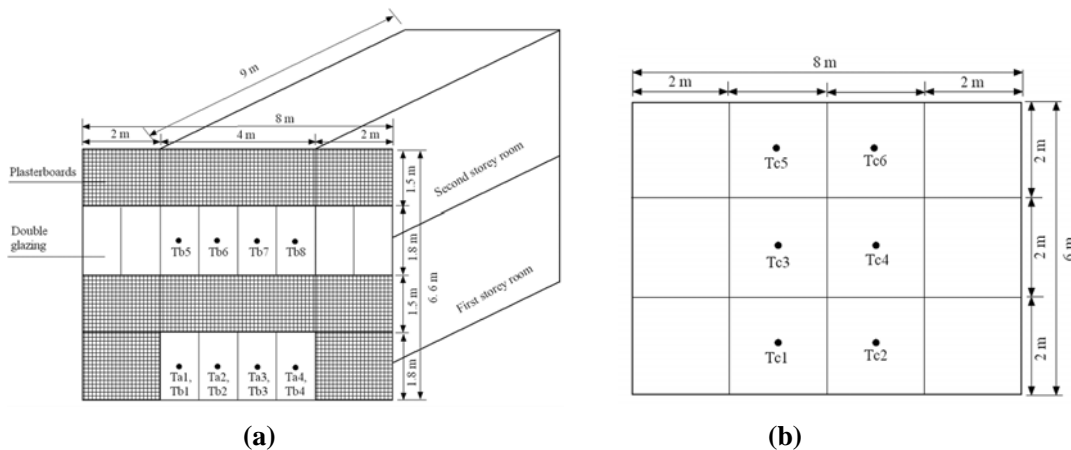


Figure 2 (a) Internal skin of the facade; (b) External skin of the facade.

Table 1 Details of the double skin glazing facade.

	Glaze pan Size	Glaze Futures
Internal skin glazing	1.0m×1.8m(high), 21mm (thick)	Double glazing, two 6mm-thick toughened glass with a 9mm-thick air gap
Outer skin glazing	2.0m×2.0m(high), 25.5mm (thick)	Double glazing, two 12mm-thick toughened glass sandwiching a 1.5mm-thick gel layer

Fire Scenarios

Three fire scenarios were shown in Table 2. Tests A and B were designed to simulate a fire located close to the facade (the distance between the fire and facade is about 0.8m). Test C was designed to simulate a fire close to the facade with a more server heat release rate, and the maximum HRR was about 2.0 MW. In Test C, two center panels (where Ta2,3 and Tb2,3 were located, shown in Figure 8) of the internal skin on the first floor were not installed. This was to simulate the condition that the internal facade had already broken and fallen out. These fire scenarios were considered to be localized fire with limited HRRs. This took into account a successful suppression from active fire protection systems.

Table 2 *Design of the three fire scenarios.*

Test	Fire Source	Maximum HRR	Comment
A	propane + diesel pool	0.7 MW	Back door of the room is open for fresh air supply
B	propane + diesel pool	1.0 MW	Back door of the room is open for fresh air supply
C	propane + wood cribs	2.0 MW	Two glass panels of the internal facade are removed; back door of the room is closed

Summary of Test Results

Both Test A and Test B show that double glazing panes on the exposed side of the internal skin broke when the temperatures reached about 600°C–800°C. Following the breaking of the inner glass of the internal skin, the outer glass of the internal skin broke at a delay of 1.5min–2.0min, depending on the fire HRR and the distance from the fire source. After the internal skin broke and fell out, flame and smoke entered the air cavity. At the end of the tests, neither the upper internal skin nor the external skin experienced any breaking in Test A and B.

Test C were performed with initial openings on the internal skin, since two of the glass panels on the internal skin were removed. Therefore, the smoke and flame could enter the cavity through the opening at the very early stage. The other two inner glass panes broke at about 5-6min. At about 9 min, the inner glass panes of the external skin broke at the lower part of the facade, as the hot air and smoke in the cavity were more likely to impinge on the external skin rather than the internal skin. After breaking of

the external skin, the intervening gel between two glass panes were exposed to fire and ignited. This resulted in breaking and partial falling of the outer glass on the external skin. The test pictures of Test C are shown in Figure 3. During the test, the temperatures of smoke plume in the cavity were not hot enough to break the internal glass on the upper floor.



(a) flame spread into the cavity;



(b)breaking of the inner glass of the external skin



(c) burning of gel layer of the external skin



(d)breaking of the external skin glazing

Figure 3

NUMERICAL STUDIES

In this paper, the CFD package Fire Dynamics Simulator (FDS) is adopted to study the smoke and flame movement from a compartment to the cavity of a double skin facade.

Five scenarios were modelled by considering either a 2.0 MW or 6.0 MW fire with different cavity depths between the internal skin and the external skin. Table 3 shows the five scenarios modelled in the FDS.

Scenario 1 was setup to simulate Test C. The fire is located in front of the facade. Scenario 2 was also a localized fire, but set in the center of the room. These two fires have a maximum HRR of 2.0MW in order to consider a possible situation when the active fire suppression system successfully react and the burning area is limited to one or two items. Scenarios 3 to 5 are setup to simulate fully developed fires when no sprinklers are installed in the building, or the sprinklers fail to control the fire spread. The fire sources are located in the center of the room.

A FDS model of the test rig is shown in Figure 4. The grid size is 0.2×0.2×0.2m in the fire room, and the grid size is 0.1×0.1×0.1m in the cavity. The HRR is assumed to develop at the fast t2 growth rate and remains at the peak value once it is reached.

Table 3 *FDS model scenarios.*

Fire Scenario	Maximum HRR	Cavity Depth	Comment
1	2.0 MW	0.8 m	Localized fire close to the facade
2	2.0 MW	0.8 m	Localized fire in the center of the room
3	6.0 MW	0.8 m	Fully developed fire in the center of the room
4	6.0 MW	1.4 m	Fully developed fire in the center of the room
5	6.0 MW	2.0 m	Fully developed fire in the center of the room

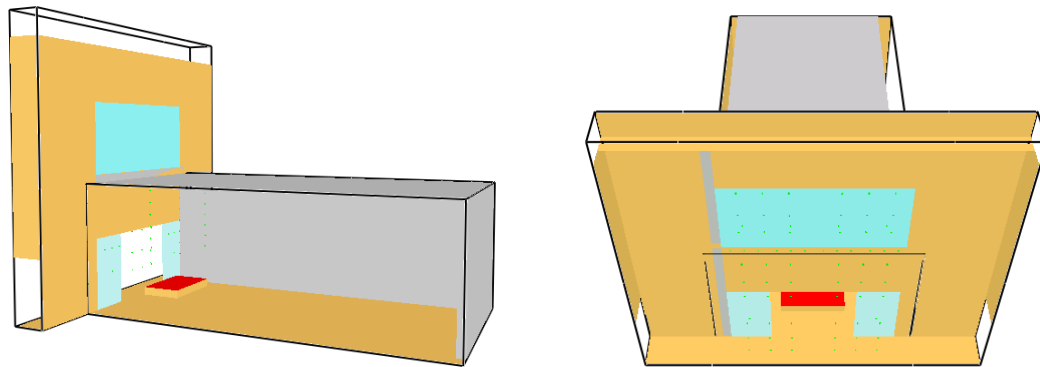


Figure 4 *FDS model of the test rig.*

Comparison with test results

Temperatures calculated in the FDS model are compared with those measured in Test C. Figure 5 shows the comparison for temperatures at different locations of glass panes. Temperatures located next to the exposed side of the internal skin for the two glaze panes are shown in Figure 5(a); temperatures located next to the unexposed side

of the internal skin on the second floor are shown in Figure 5(b); Figure 5(c) shows temperatures located next to the inner side of the external skin. The temperature curves predicted by the FDS model have the similar trends to the measured temperature curves. The measured curves exhibit more fluctuation and the peak values are slightly higher than the modelled. In general, the modelled results are in good agreement with the measured temperatures.

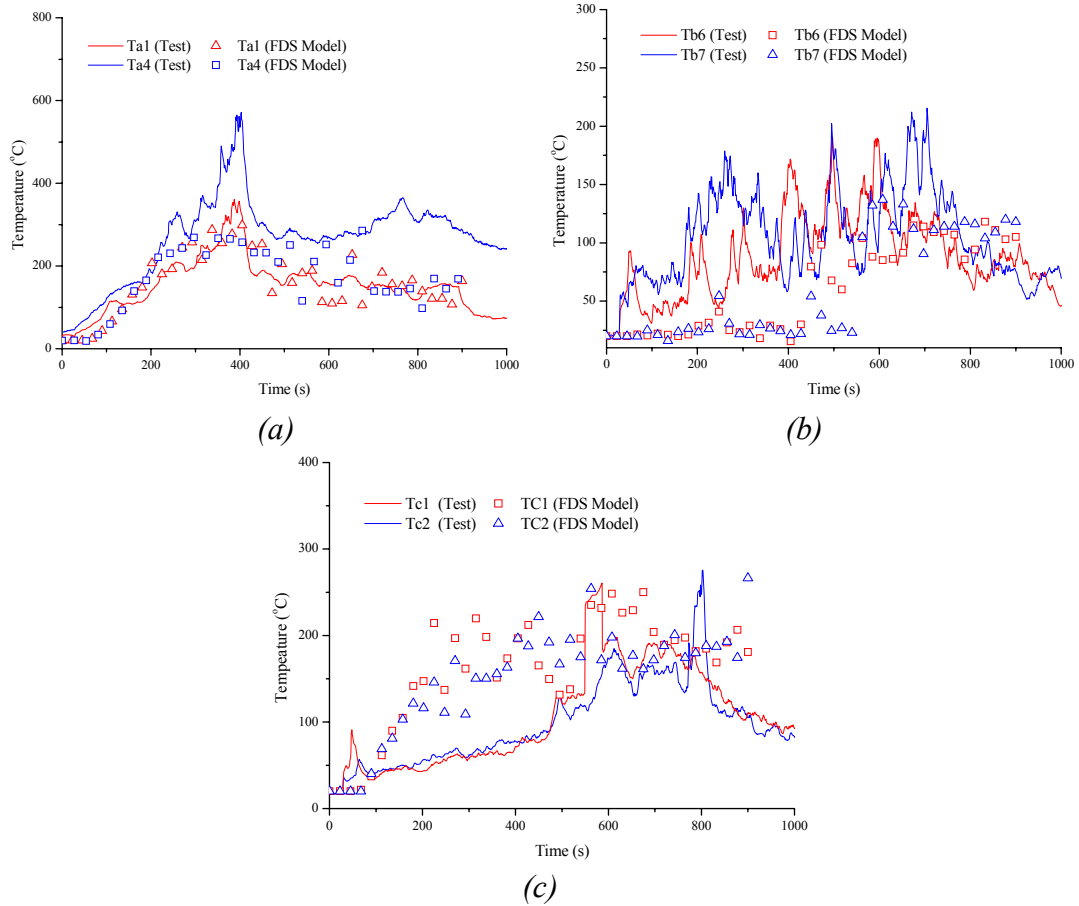
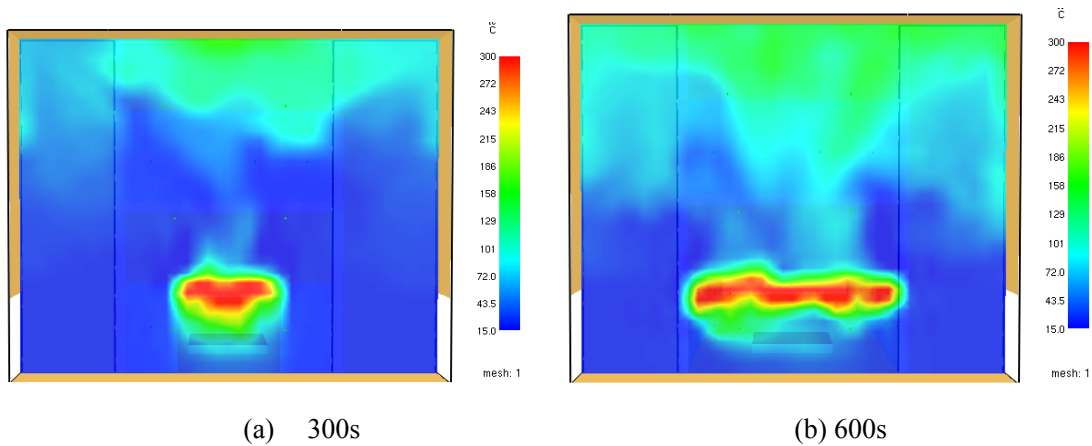
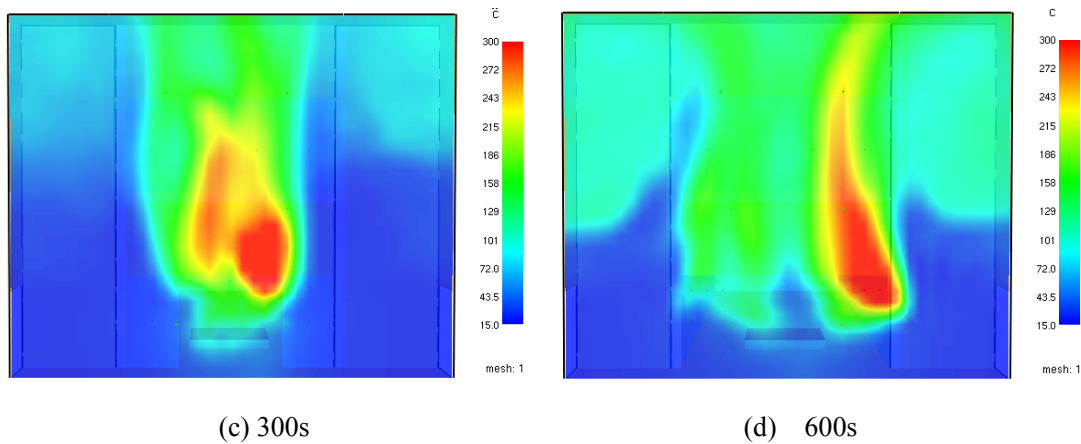


Figure 5 Comparison of measured and modelled temperatures.





(a) and (b) located at the inner skin; (c) and (d) located at the external skin.

Figure 6 Temperature profiles calculated in FDS for Scenario 1:

Temperature profiles next to the internal skin and the external skin of the facade calculated in the FDS model are shown in Figure 6.

Effect of fire source

Figure 7(a) and 7(b) show the vertical temperature profiles next to internal and external panes in the cavity for Scenario 1 and 2, respectively. The fire is set with a maximum HRR of 2.0MW. It could be observed that if the fire source is located close to the facade, temperatures next to the external facade could get up to about 400°C. This could possibly break the external skin. However, if the fire is located in the center, the temperatures next to internal and external panes are less than 300°C. No glass will break at these temperatures. In Both scenarios, the temperatures next to the internal skin above the fire room are less than 100°C, which could not break the internal panes on the above floor.

Figure 7(c) show the vertical temperature profiles next to internal and external panes in the cavity for Scenario 3. It is a fully-developed fire with a maximum HRR of 6.0MW. The temperatures next to the external panes rise up to about 600 and the external could break at these temperatures. However, the temperatures next to the internal panes above the fire room remain low and could not break the glass panes.

Effect of cavity depth

Figure 7(c), 7(d) and 7(e) show the vertical temperature profiles next to the internal and external pans in the cavity at the steady burning stage for Scenario 3, 4,

and 5. It is observed that, for a double-skin facade with a narrow cavity depth, the smoke and hot air tend to hit the external skin directly after it moves out of the fire room. These temperatures could cause the external panes to break. However, the breaking of the external glass pane would benefit exhausting the heat from the cavity.

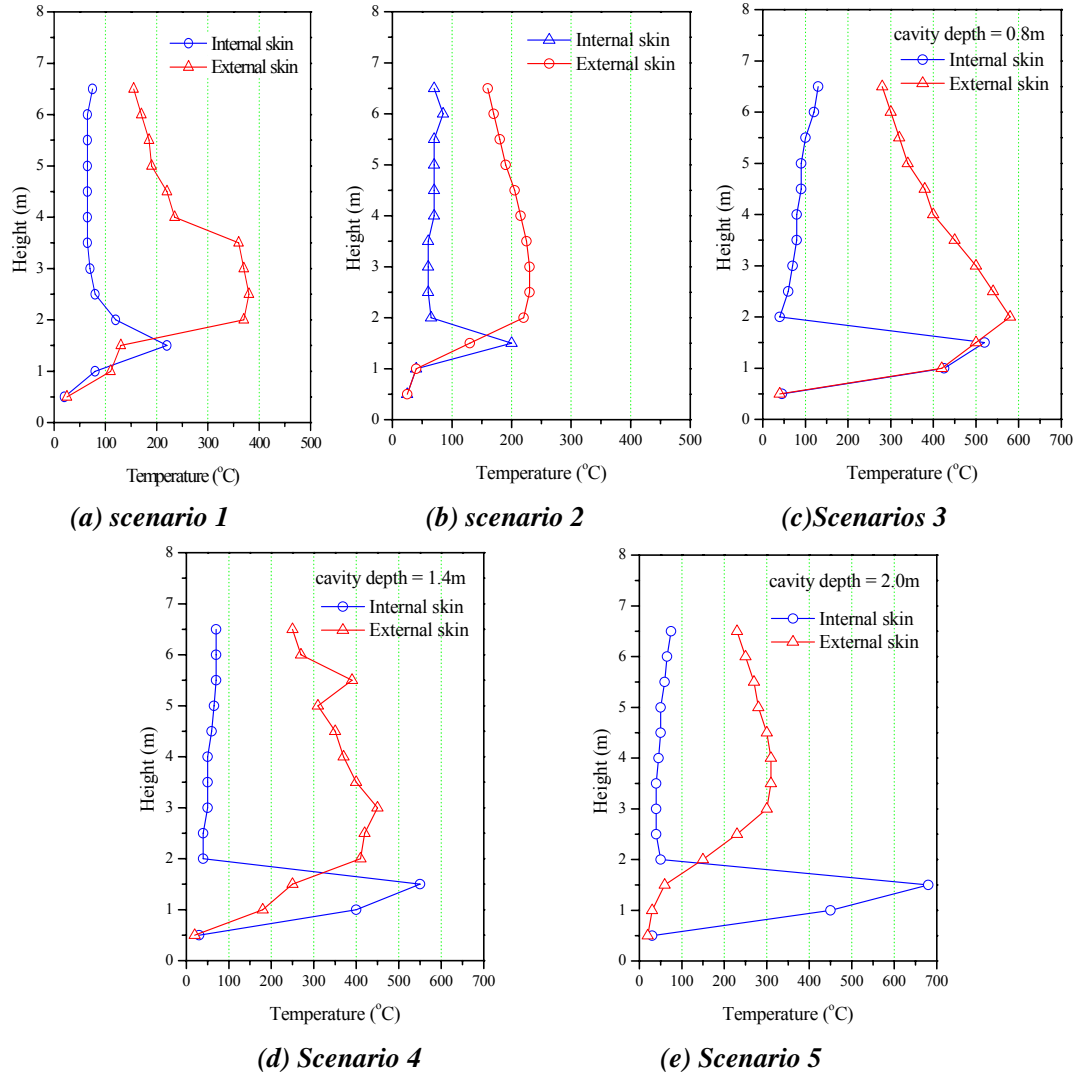


Figure 7 Vertical temperatures at internal and external skins.

When the cavity depth increases, the temperatures on the external would decrease. However, the smoke plume did not exhibit any attaching to the internal skin for wide cavity. This is possibly because the distance between the top of the vent and the ceiling is large in the setup of the test rig. This aspect keeps the hot plume move away from the internal skin and hit upon the external skin. On the other hand, the two-storey rig would not be tall enough to cause strong stack effect in cavity. Therefore, the air entrainment is not sufficient to push the plume against the internal

skin. In the future, the effect of the vent-to-ceiling height and the test rig height will be studied.

The slice views of temperature profiles for the scenarios are shown in Figure 8.

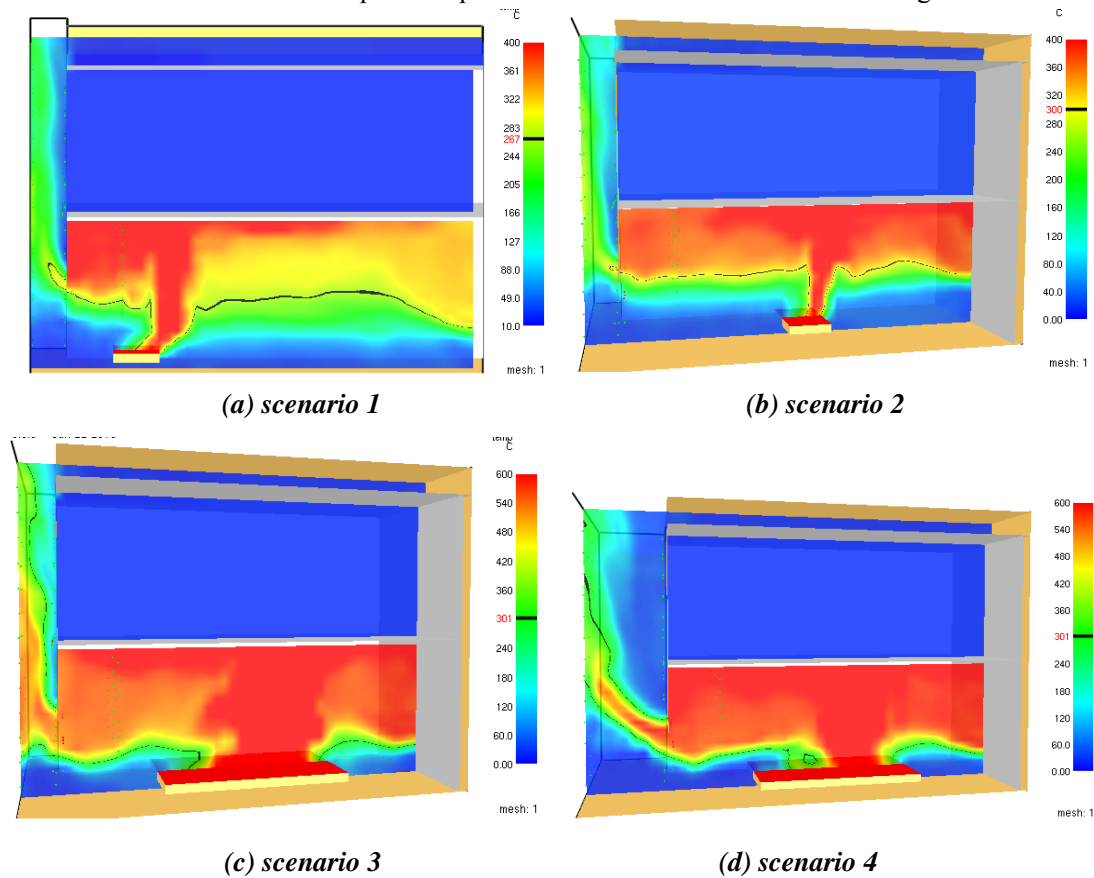


Figure 8 Slice view of temperature profiles.

Conclusions

Based on the experimental and numerical work conducted in this research, the following conclusions can be drawn:

1. Full-scale experimental fire tests show that the double glazing with 6-mm-thick toughened glass would break at a temperature of about 600°C–800°C. The breakage time of glass depended on the fire HRR and distance from the fire source.

2. The modelled temperatures next to the external and internal skins in Scenario 1 are in good agreement with measured temperatures in Test C.

3. Numerical modellings suggest that for a center-located fire with a maximum HRR of 2.0MW, the hot air and smoke plume should not be able to break the external skin with a narrow cavity depth of 0.8m; while a fire source located close to the facade could cause the external skin to break. For a fully-developed fire with a

maximum HRR of 6.0MW, the temperatures of hot air and smoke in cavity are high enough to break the external skin.

4. For fully-developed fires, the hot air and smoke plume hit the external panes after leaving the fire room, without any attaching to the internal panes. The height of the two-storey rig is not able to cause strong stack effect in the cavity. The internal panes would have low temperatures and could not break. The effect of the vent-to-ceiling height and the test rig height will be studied in the future.

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