Experimental Study on the Characteristics of Temperature Field of Fire Room under Stack Effect in a Scaled High-rise Building Model

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ABSTRACT：

A set of experiments were conducted in a scaled building model with 12 floors to study on the temperatures of fire room under stack effect in a high-rise building. The fuel mass loss rate, radiant flux, heat flux and temperatures in the atria and fire room at the first floor were experimentally investigated. The flames of pool fires in room are tilted towards the staircase under the air flow induced by the stack effect. The mass loss rate of fuel is influenced slightly by the position of window opened in the staircase, while the temperature distribution in the atria and fire room is different in the opened and closed staircases. The hot smoke temperatures in the atria and fire room at the first floor increase with an increasing pool size. The upper hot smoke temperatures in the atria are higher than those in the fire room in cases with an opened staircase. Compared different positions of the window opened in the staircase, it can be found that the upper hot smoke temperatures in the atria in cases with the 3rd floor window opened are the highest due to the weaker stack effect. In the closed staircases, the upper hot smoke temperatures in the fire room are great higher than these in the atria at the first floor. Besides, the radiant flux and heat flux of the left sidewalls of staircase in an opened staircase are higher than those in a closed staircase, due to the tilted flame. The results obtained in this paper may be used for the safety design of the room in high-rise buildings.

KEYWORDS：stack effect, high-rise building, compartment fire, temperature distribution, radiation.

INTRODUCTION

More and more high-rise buildings have been constructed in the world. Fire safety of these high-rise buildings has been attracted public attention owing to many catastrophic fire accidents [1-3]. The hot smoke produced by fire source may flow into the staircases and spread upward rapidly by stack effect in the high-rise building. Stack effect [4-5] is the phenomenon, with air entering through openings in lower floors, flowing upward in the building, and leaving through openings in upper floors, which results from density difference between hot inside air and cold outside air [6]. If a fire occurs in a high-rise building, not only the smoke movement will be accelerated by stack effect in those vertical shafts, seriously threatening to personnel safety evacuation, but also the air flow pattern in the room adjacent to a staircase is affected by the stack effect, and a plenty of fresh air is sucked into the fire room by the stack effect, providing sufficient oxygen for combustion.

Many researchers have studied smoke movement induced by the stack effect in shafts and staircases of high-rise building spaces in the past few years [7-18], including neutral plane position prediction [7, 8], hot smoke movement mechanism [9-14], rise-time of buoyant plumes [15, 16] and pressure and temperature distribution [17, 18]. Little attention has been focused on the influence of the airflow induced by stack effect on the fire. Satoh et al. [19, 20] investigated the interaction between the airflow induced by stack effect and the flame of gas fire located on the ground at the center of shaft in a reduced shaft model, and discussed the effect of the inlet opening arrangements on flame tilt direction, flame tilt angle and flame length.

Actually, it is also a very common scenario when the fire occurs in the room adjacent to a staircase in a high-rise building. The characteristics of temperature field of fire room are are significant for the safety design in the high-rise buildings, while, these parameters in the fire room under stack effect have not been studied in this circumstance. Besides, generally, many windows are fixed in the staircase to connect to the ambient environment for lighting and ventilation. The positions of these windows opened influence the stack effect magnitude in the staircases, which further affects the air flow pattern and temperature distribution in the fire room. In this paper, to study the influence of the height of window opened on the temperature distribution of the fire room adjacent to the staircase, a set of experiments were conducted in a 1/3 scaled building model.

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EXPERIMENTAL FACILITY

The 1/3 scale building model [18] was established in 2009 according to the principle of similitude [21, 22], as shown in Fig. 1 [23]. This model with 12 floors is 12.2 m (high) × 2.6 m (long) ×1.5 m (wide). The ground floor is 1.2 m in height and the other floors are 1.0 m in height. The back wall of staircase of each floor has a window connected to outside with the size of 0.9 m high × 0.7 m wide. The first floor has three doors with the size of 0.6 m high × 0.4 m wide. The left and front sidewalls of model are made of fire-resistant glass with 12 mm thickness for observation, and the other parts of staircase are made of steel plate with 2 mm thick. The additional 8 mm thick fireboard is used as the inner lining of fire room and atria at the first floor for thermal insulation.

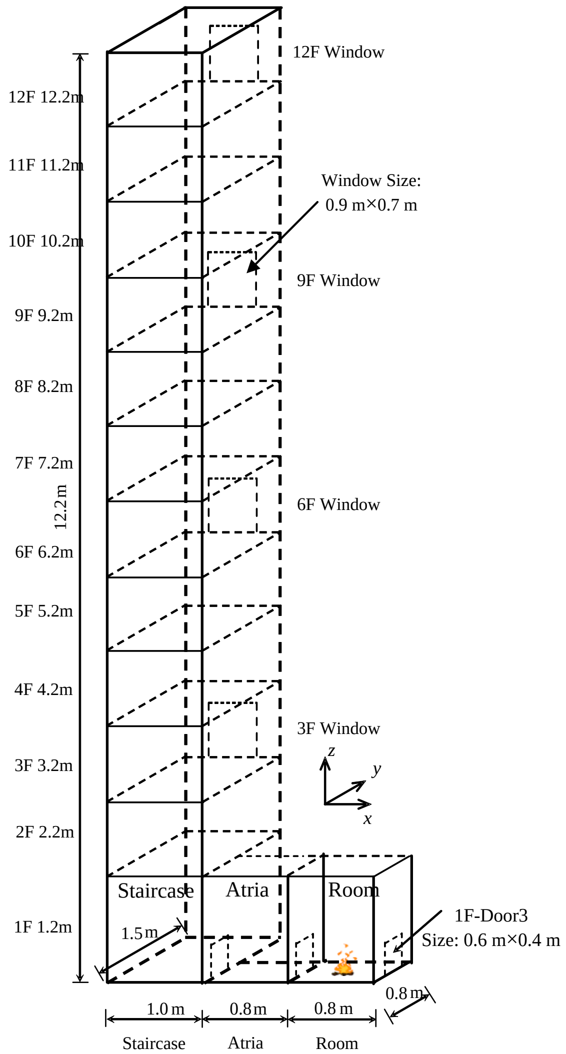
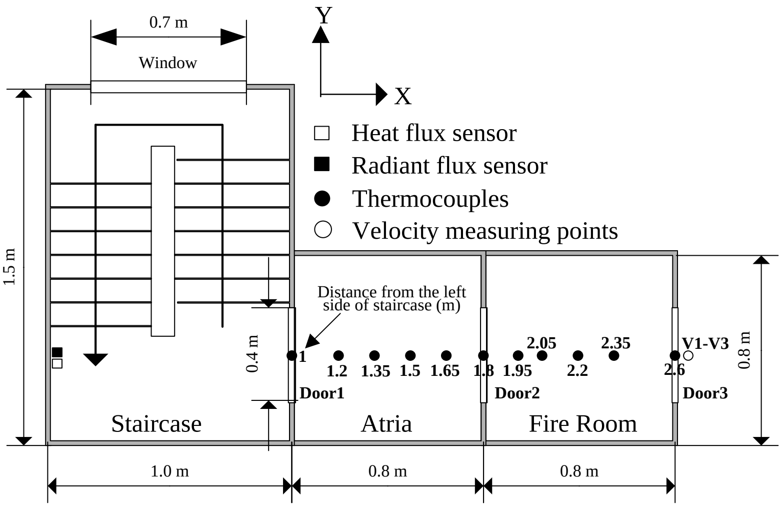


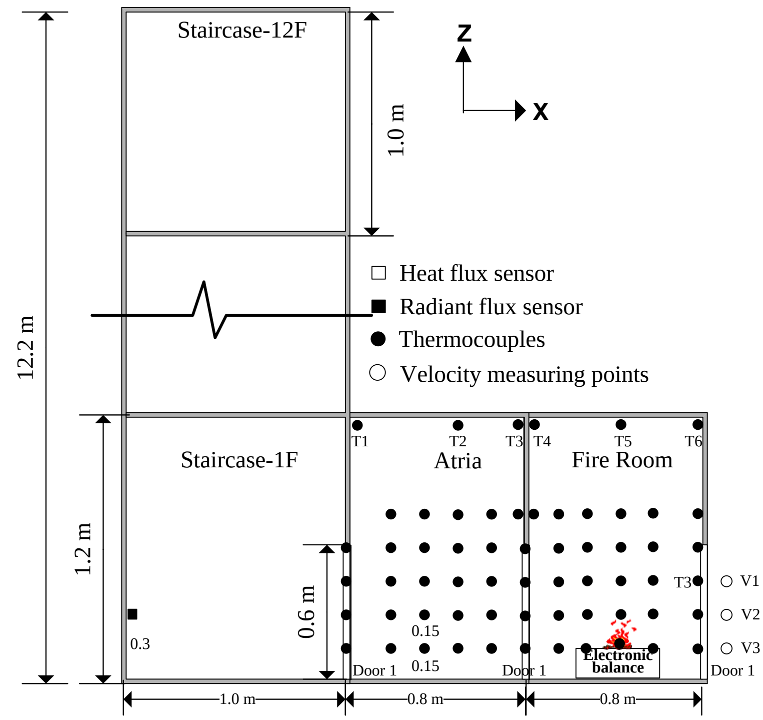
Fig. 1. Schematic of 1/3 scaled staircase building model [23]

The temperatures of hot gases in the room and atria at the first floor were measured by K-type fine wire thermocouples with the diameter of 1 mm. Three velocity probes of hot-wire anemometers (Kanomax, KA12) at a 15 cm vertical interval were installed 5 cm away from the right of door 3 to measure airflow speed with sampling intervals of 1 s. The radiant flux sensor (Captec Enterprise TS-30) and heat flux sensor (Captec Enterprise HS-30B) were located closed to the left sidewalls of staircase at a height of 0.3 m to measure the total radiant flux and total heat flux from the hot smoke and flame. The heat flux sensor measured the total radiation heat and the convective heat from the flame and hot smoke, while the radiant flux sensor just measured the total radiation heat. The detailed locations of these thermocouples, velocity probes, radiant flux sensor and heat flux sensor are shown in Fig. 2. Pool fires were set as fire sources, and heptane was used as fuel. The size of square pool is 10 cm, 15 cm, 20 cm and 25 cm. These pools were made by 2 mm thick steel board. Their depths were all 4 cm, and the initial thickness of the fuel was 2 cm for each case. The mass of burning pool fires were recorded by a digital electronic balance with an accuracy of 0.01 g. A Digital Vidicon and a Digital Camera were used to record the flame development in the room. Three doors in the first floor were always opened in each case. The windows at the 3rd, the 6th, the 9th and the 12th floor were selectively opened, respectively. Only one window was opened to connect the outside and other windows were closed in each case. Ambient temperature was about 30-32 °C. Each case was repeated once, and the results showed that the repeatability was good.

For this series of experiments, we have investigated the smoke movement mechanisms in the staircase [23]. In this paper, we focus on discussion the temperature distribution and radiation of the fire room under stack effect in a staircase.



(a) top view



(b) side view

Fig. 2. Locations of the measured points

RESULTS AND DISCUSSION

Typical Fire Behavior in the Room

The development of flame shapes of different pool fires was recorded in each case. The typical flame shapes of 20 cm pool size at the fully developed period are show in Fig. 3. The rectangular black area in the middle of the pictures is the connection part of fire room and atria at the first floor. The flames tilt toward the staircase owing to the airflow induced by the stack effect in cases with an opened staircase, as shown in Fig. 3 (a), (b), (c), and (d). By comparing these four pictures, it can be found that the flame length in case with the 12th floor window opened is slightly longer, due to a larger induced wind speed V_{avg} through door 3 on the right side of the fire room. Whereas the flame tilt angle (the angle between the centerline of flame region and vertical direction) in case with the 3rd floor window opened is slightly smaller owing to lesser wind speed V_{avg}. In cases with a closed staircase, the flame tilts slightly toward the staircase because of the lack of stack effect, as shown in Fig. 4. The flame shape of 20 cm pool size ejects from the door 2 at the left of fire room. By contrast, the flame of 25 cm pool size fills the entire room and part of the flame spread towards the door 3, resulting from more fresh air required to maintain the combustion of the bigger pool. At the same time, plenty of black smoke was produced due to insufficient oxygen and the flame tip located in the upper part of the fire room could almost not be seen.

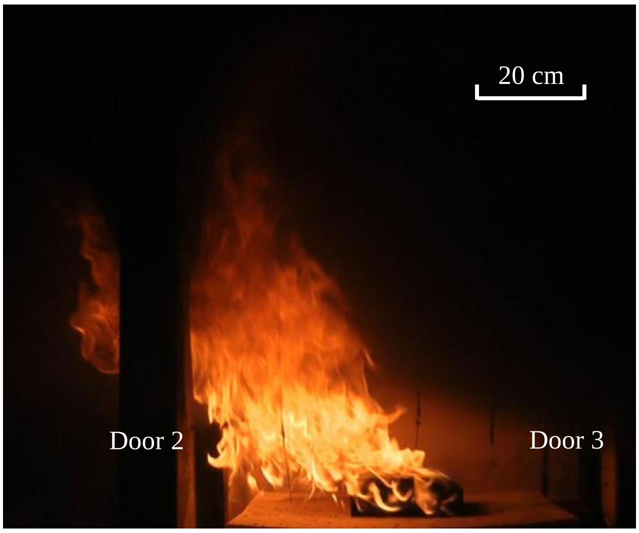
(a) Flame shape of 20 cm pool size with the 12th (12.2 m) floor window opened at t=350 s

(b) Flame shape of 20 cm pool size with the 9th (9.2 m) floor window opened t=350 s

(c) Flame shape of 20 cm pool size with the 6th (6.2 m) floor window opened at t=350 s

(d) Flame shape of 20 cm pool size with the 3rd (3.2 m) floor window opened at t=350 s

Fig. 3. Typical flame shapes of 20 cm pool size in the opened staircases



(a) Flame shape of 20 cm pool size at t=300 s

(b) Flame shape of 25 cm pool size at t=220 s

Fig. 4. Typical flame shapes of 20 and 25 cm pool sizes in the closed staircases (all windows closed)

Mass Loss Rate

The mass loss rates versus time of 20 cm pools are shown in Fig. 5. It can be seen that the mass loss rate is relatively small at the early slow growth period [24]. Then it increases rapidly and reaches a peak at the fully developed period. The maximum in case with a closed staircase is about 4.0 g/s at 330 s, which is higher than that in an open staircase. The reason is that most of the flame of pool fire is within the fire room and the unburned heptane in the pan receives more heat feedback from flame, upper hot smoke and sidewalls, leading to bigger evaporation rate and combustion rate [25]. By comparing the maximum mass loss rates of 20 cm pool size in opened staircase, it can be found that the maximum mass loss rates have slight difference under the action of stack effect, which indicates that the mass loss rate of fuel is influenced slightly by the position of window opened in the staircase. For other pool seizes, the similar results are obtained. More about the fuel mass rate of pool fires under stack effect are presented in the reference [23]. The calculated heat release rate of pool fires at the fully developed period are shown in Table 1.

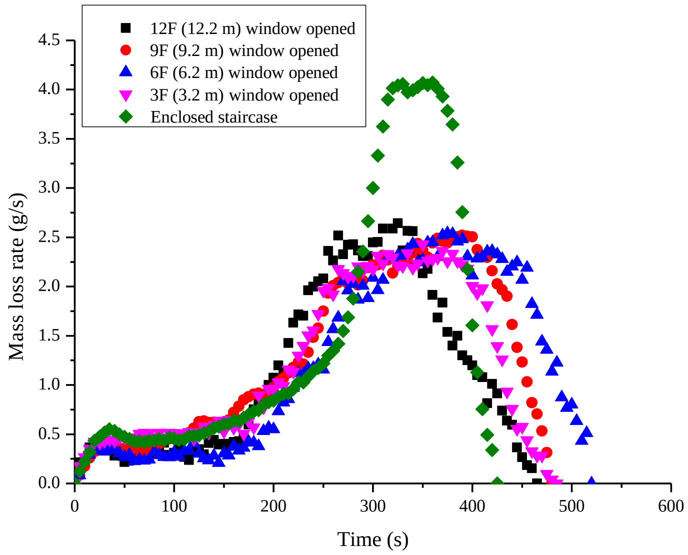


Fig. 5. Fuel mass loss rate versus time of 20 cm pool size in different cases

Table 1. Heat release rate of pool fires at the fully developed period

Window opened location	10 cm pool	15 cm pool	20 cm pool	25 cm pool
The 12th floor window opened	36.9 kW	63.1 kW	93 kW	152.1 kW
The 9th floor window opened	33.5 kW	59.2 kW	89.9 kW	140.9 kW
The 6th floor window opened	32.4 kW	56.6 kW	89.8 kW	138.4 kW
The 3rd floor window opened	28.4 kW	56.9 kW	87 kW	135.2 kW
Enclosed staircase	38.3 kW	79 kW	161.5 kW	287.8 kW

Temperatures in Atria and Fire Room

The thermocouples T1-T6 were located 5 cm below the ceiling of the atria and fire room at the first floor, respectively. The temperatures of thermocouple T2 and T5 of 20 cm pool sizes in the opened and closed staircases are show in Fig. 6. In a case with the opened staircase, at the early slow growth period, the flame is in the fire room because of the weaker stack effect. Thus the temperature of T5 rises first. As burning time passed, more hot smoke spread into staircase, the stack effect became stronger and the flame tilted toward the atria (the 1st floor) owing to the wind speed, therefore the temperature of T2 begins to increase and the temperature of T5 starts to decrease, due to the cooling effect of air flow sucked into the fire room [26]. It also can be found that the temperatures of thermocouple T2 and T5 in case with the 3rd floor window opened are higher than those in case with 9th floor window opened, resulting from the relatively weaker stack effect. In a case with the closed staircase, the flame tilted slightly toward the atria (the 1st floor), since the temperatures of T2 and T5 increase successively after ignition, while the temperature of T2 is far less than the temperature of T5. The temperature of T2 increases rapidly from 300 s to 340 s, because the flame ejected into the atria. To compare these three cases, it can be shown that the temperature of the ceiling of fire room is about 100 ^{o}C under the action of stack effect in the opened staircase. However, the temperature of the ceiling of fire room is around 650 ^{o}C in the closed staircase.

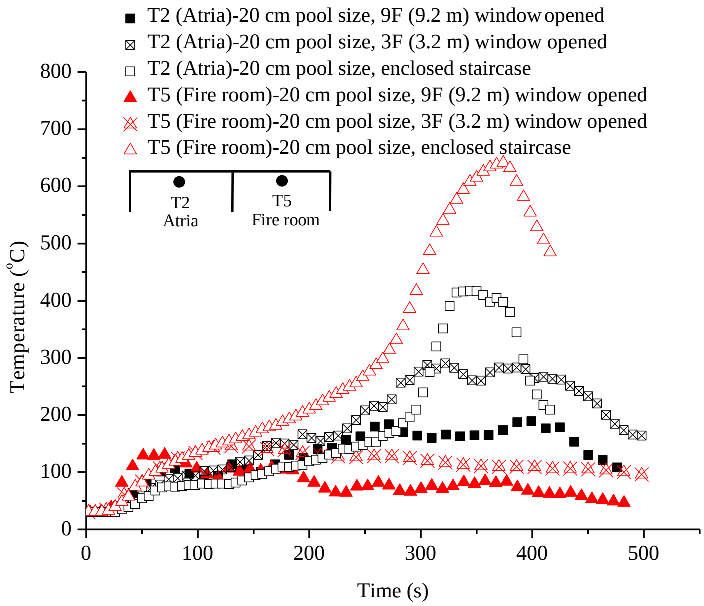


Fig. 6. Temperatures of thermocouple T2 and T5 versus time of 20 cm pool size in the opened and closed staircases

The ceiling temperatures of the atria and fire room (the 1st floor) of 20 cm pool size with the 9th window opened are shown in Fig. 7. It can be seen that the temperatures of T4, T5 and T6 in the fire room are similar and almost maintain a constant at the fully developed fire stage (300 s - 400 s), but the temperatures of T1, T2 and T3 in the atria (the 1st floor) are different. The temperature of T1 is the highest and about 180 °C, while that of T3 is the lowest and about 130 °C, and actually the difference between them is not significant. The reason is that the tilted smoke plume was easy to gather at the top left region of the atria under the action of stack effect. Besides, it is obviously observed that the ceiling temperatures of the atria are constantly changing in the process of the flame tilt toward the atria. As shown in Fig. 7, the temperatures of T1 and T2 reach a peak at 260 s, and then they decrease to a stable state at the fully developed fire stage, and then reach another peak at 400 s. While the temperature of T3 reaches a peak at 260 s, and then maintains almost a constant for a period. The similar results are obtained in other cases with the opened staircases.

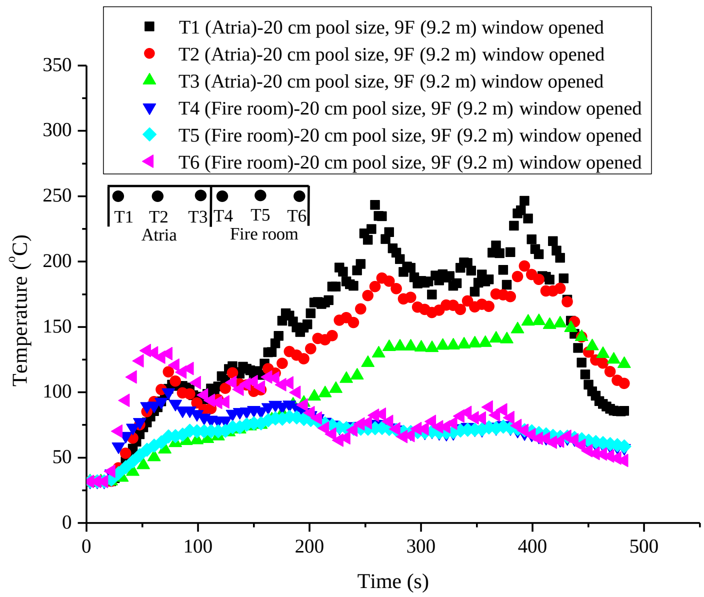
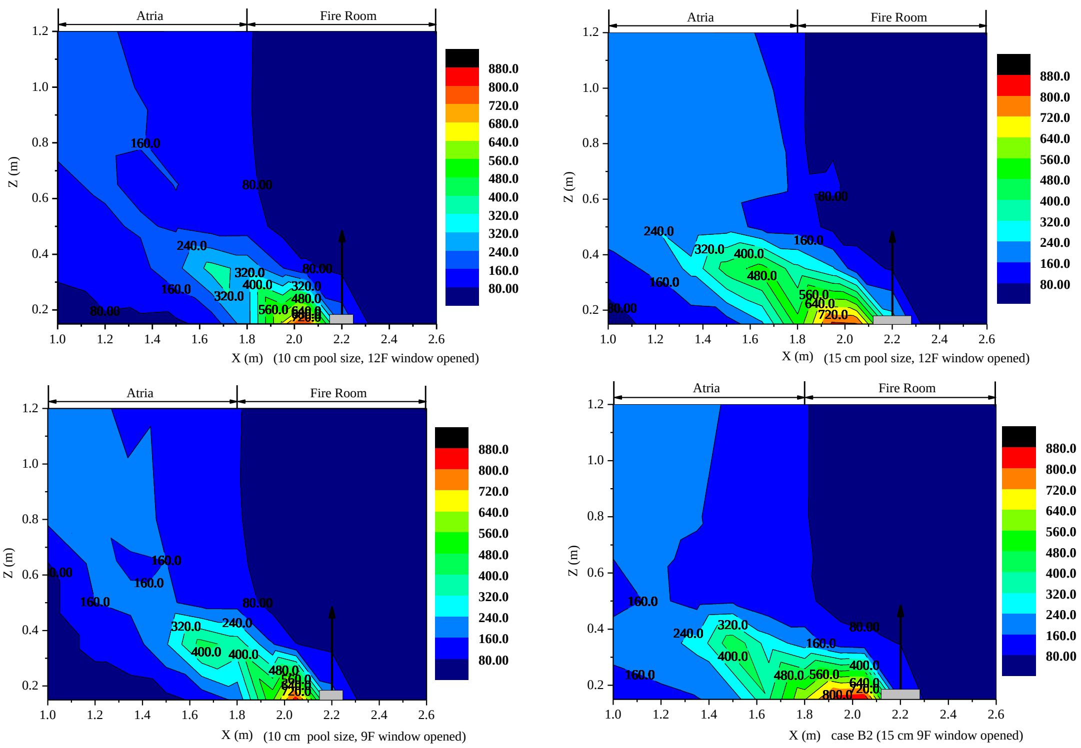


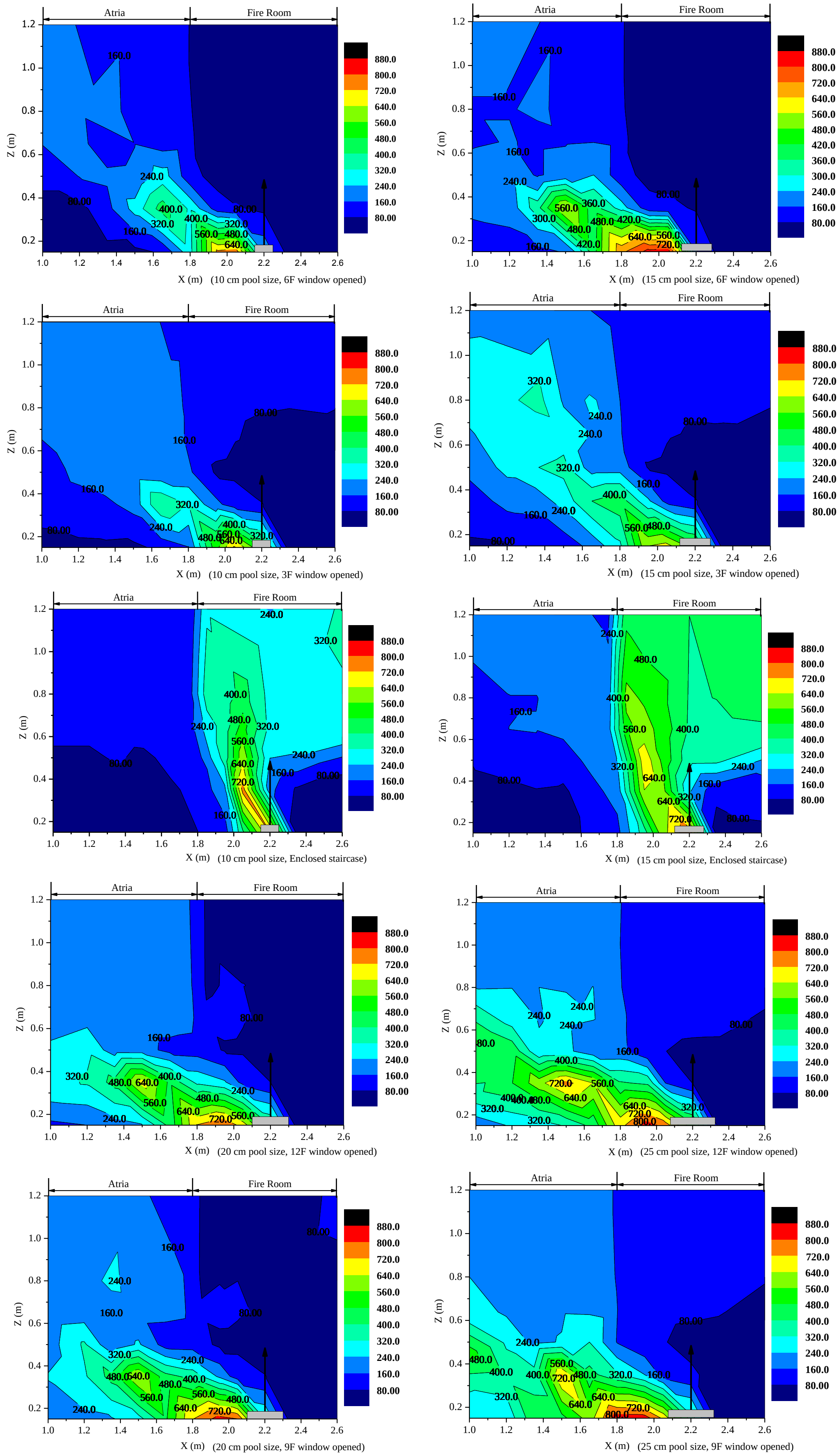
Fig. 7. The ceiling temperatures of the atria and fire room of 20 cm pool size with the 9th (9.2 m) window opened

When the mass loss rate, total radiant flux and total heat flux reached the maximum and maintained an almost constant value at the fully developed fire stage. The average temperature rise of the atria and fire room (the 1st floor) during this period in all cases is shown in Fig. 8. It can be seen that the temperature distribution in the atria and fire room is different in all cases. In cases with an opened staircase, the lower flame tilts toward the atria owing to the stack effect, and the flame region increase with an increasing pool size. Besides, it can be seen obviously that the upper hot smoke temperatures in the atria are higher than those in the fire room. Taking 20 cm and 25 cm pool sizes for examples, the upper hot smoke temperatures in the atria are more than 160 ^{o}C, while those in the fire room are less than 160 ^{o}C. The opened window position has a significant effect on the temperature distribution in the atria and fire room. In cases with windows opened at the 12th, 9th and 6th floor, the smoke temperatures of 10, 15, and 20 cm pool sizes in the fire room are all less than 80 ^{o}C, resulting from the mixing process between the hot smoke and the cooling air induced by the stack effect, so the hot smoke could be modeled as one zone, while those of 25 cm pool size with larger heat release rate, the upper hot smoke temperatures are higher than the lower air zone, and thus the hot smoke could be modeled as two zones. In the same way, for 10 and 15 cm pool sizes, the smoke temperatures in the left region of the atria are higher than those in the right region, while for 20 and 25 cm pool sizes, the smoke temperatures in the whole atria are similar and could be modeled as one zone.

In cases with windows opened at the 3rd floor, the upper hot smoke temperatures in the fire room are higher than the lower air zone, while the smoke temperatures in the left region of the atria (the 1st floor) are higher than those in the right region. Besides, comparing with the cases with the other windows opened, the temperature distribution of the atria in cases with the 3rd window opened is obvious different. For 20 cm pool size, the upper hot smoke temperatures of the atria in case with the 3rd window opened are more than 240 ^{o}C, while those in other cases are all less than 240 ^{o}C. A possible explanation for this phenomenon is that the wind speed of 20 cm pool size induced by stack effect is significant minimum in case with the 3rd window opened, as show in Fig. 3. On one hand, the flame tilt angle is smaller and the hot smoke is easy to gather at the upper of the atria. On the other hand, the air mass flow sucked into the atria is small owing to lesser wind speed V_{avg} and thus the cooling effect is poor. Considering these two aspects, the upper hot smoke temperatures in the atria in cases with the 3rd window opened are the highest as shown in Fig. 8.

In cases with the closed staircases, the upper hot smoke temperatures in the atria and fire room (the 1st floor) increase with an increasing pool size, and the values are higher than the lower air zone, thus the hot smoke could be modeled as two or more zones. Besides, it is obviously observed that the upper hot smoke temperatures in the fire room are great higher than those in the atria. The flame of 20 cm pool size ejected into the atria as shown in Fig. 4(a), resulting in a significantly larger temperature rise in the atria. For 25 cm pool size, the flame filled the entire room and part of the flame spread towards the outside as shown in Fig. 4(b), so the whole fire room temperatures are very high. The upper hot smoke temperature in the fire room is more than 640 ^{o}C, and the temperatures at the upper of door 3 on the right side of fire room is above 400 ^{o}C, which indicates the flashover fire may occur in the fire room [27].




Atria
Fire Room
Z (m)
X (m) (10 cm pool size, 6F window opened)
X (m) (15 cm pool size, 6F window opened)
X (m) (10 cm pool size, 3F window opened)
X (m) (15 cm pool size, 3F window opened)
X (m) (10 cm pool size, Enclosed staircase)
X (m) (15 cm pool size, Enclosed staircase)
X (m) (20 cm pool size, 12F window opened)
X (m) (25 cm pool size, 12F window opened)
X (m) (20 cm pool size, 9F window opened)
X (m) (25 cm pool size, 9F window opened)

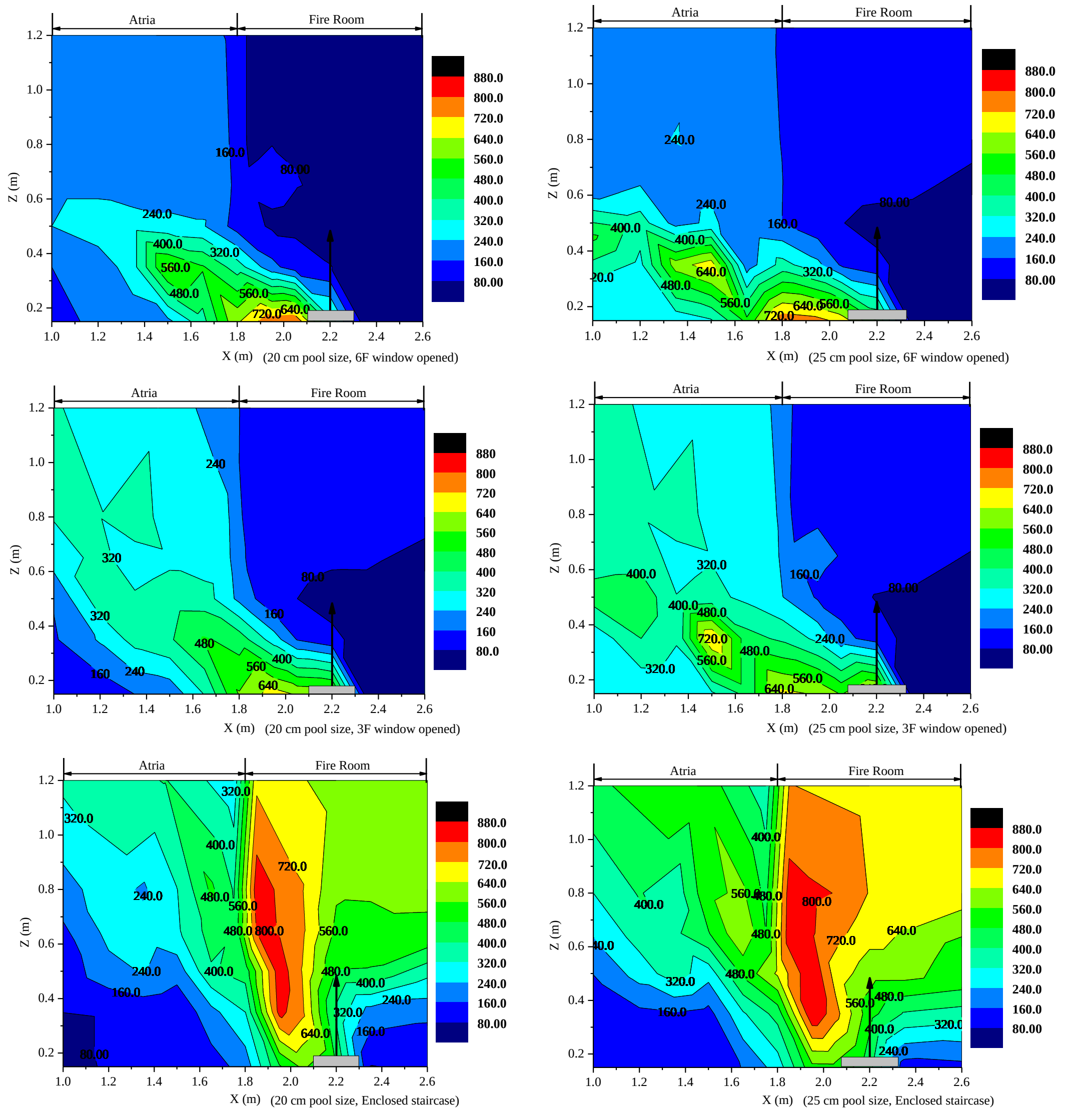
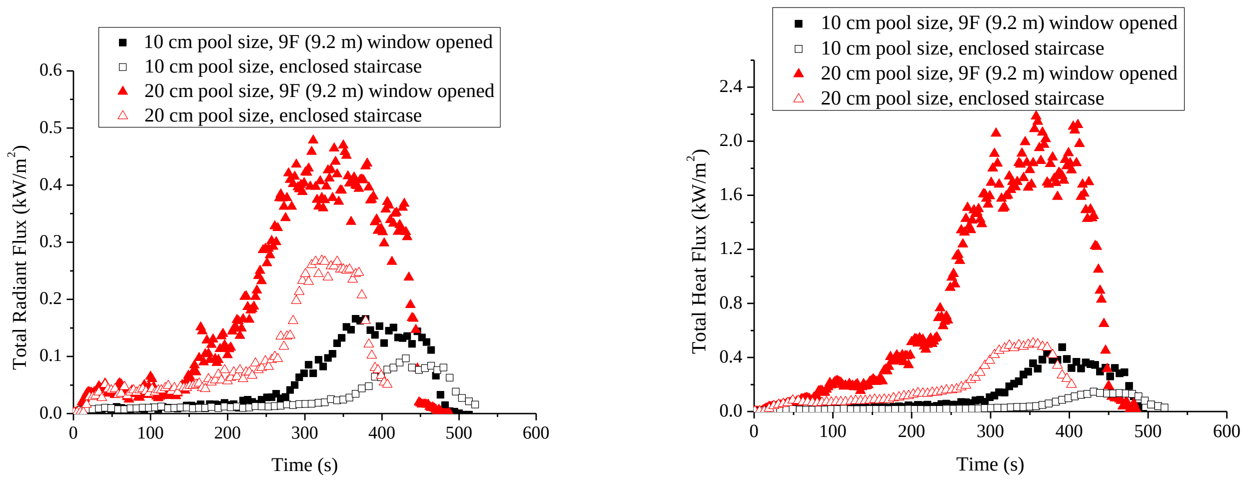


Fig. 8. Temperature rise of the atria and fire room at the fully developed fire stage in all cases

Radiant Flux and Heat Flux

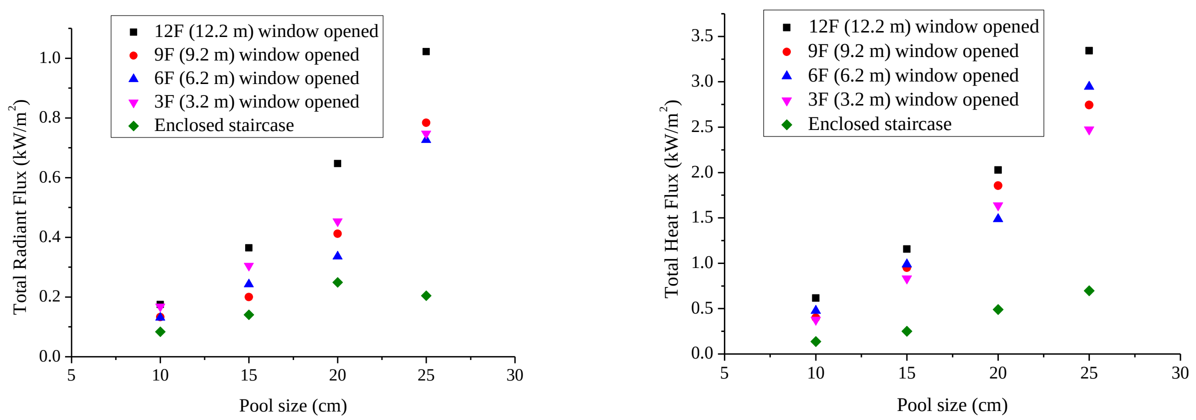
Fig. 9 shows the measured total radiant flux and total heat flux versus time of 10 cm and 20 cm pool sizes in the opened and closed staircases. It can be seen that the radiant flux and heat flux maintain a steady stage at the early burning period, and then reach rapidly a peak. In cases with an opened staircase, the radiant flux of 20 cm pool size increases to the maximum first. As shown in Fig. 9(a), the total radiant flux of 10 cm pool size reaches a peak of 0.18 kW/m^2 at 360 s and that of 20 cm pool size reaches a peak of 0.42 kW/m^2 at 300 s. After reached its maximum, the measured values of 20 cm pool size have a larger fluctuation owing to the influence of the tilted flame oscillation, while those of 10 cm pool size have a smaller fluctuation. The reason is that the flame length of 20 cm pool size is greater and the distance between flame front and radiant flux sensor is relatively shorter. In cases with the closed staircase, the total radiant flux of 20 cm pool size reaches a peak of 0.22 kW/m^2 at 230 s, and the maximum is lower than that in opened staircase. The total heat flux has a similar variation trend as shown in Fig. 9(b).



(a) Total radiant flux versus time (b) Total heat flux versus time

Fig. 9. Total radiant flux and heat flux versus time of 10 cm and 20 cm pool sizes in the opened and closed staircases

The time-average total radiant flux and total heat flux at the fully developed fire stage in all cases are shown in Fig. 10. It can be seen that the time-average total radiant flux and total heat flux in cases with the opened staircases are higher than those of the closed staircases for the same pool size. In the cases with an opened staircase, the flame tilted toward the staircase owing to the stack effect, and in the meantime, amounts of hot smoke flowed into the staircase. When in the cases with a closed staircase, the stack effect was disappeared, and thus the flame tilted slightly. Only part of hot smoke flowed into the staircase, and the other parts flowed out through the door 3. As a result, the measured values of total radiant flux and total heat flux from the flame and hot smoke in cases with the closed staircases are the lowest. Comparing the total radiant flux and total heat flux of 20 cm and 25 cm pool sizes in the closed staircase, the total radiant flux of 20 cm pool size is higher than that of 25 cm pool size as shown in Fig. 10(a), but the total heat flux has the opposite trend as shown in Fig. 10(b). A possible explanation is that the flame of 20 cm pool size ejected to the atria (Fig. 4(a)) and was closer to the radiant flux sensor, while the flame of 25 cm pool size spread towards the outside (Fig. 4(b)) and was far from the radiant flux sensor. To further analyze the data shown in Fig. 10, the time-average total radiant flux and total heat flux in cases with the 12th window opened keep the highest, because of longer flame length and higher wind speed as shown in Fig. 3 (a). Besides, for the same pool size, the values in other cases with the opened window at the 9th, 6th, and 3rd floor fall in the range of the cases with the opened window at 12th floor and the case with the closed staircase, while these values have no obvious variety regulation.



(a) Time-average total radiant flux (b) Time-average total heat flux

Fig. 10. Time-average total radiant flux and heat flux at the fully developed fire stage in different cases

Conclusion

In this paper, to study the influence of the height of window opened on the temperature distribution of the fire room adjacent to a staircase, a set of experiments were conducted in a 1/3 scaled building model. The temperatures in the atria and fire room (the 1st floor) have been experimentally investigated.

The flames of pool fires in room tilt towards the staircase under the air flow induced by the stack effect. The mass loss rate of fuel is influenced slightly by the position of window opened in the staircase, while the temperature distribution in the atria and fire room is different in the opened and closed staircases. The hot smoke temperatures in the atria and fire room increase with an increasing pool size. In the opened staircase, the upper hot smoke temperatures in the atria are higher than those in the fire room. Compared different positions of the window opened in the staircase, the upper hot smoke temperatures in the atria in cases with the 3rd window opened are the highest owing to the weaker stack effect. In the closed staircases, the upper hot smoke temperatures in the fire room are great higher than these in the atria. The flame ejects into the atria and the flashover fire may occur in the fire room for the bigger pool sizes.

The radiant flux and heat flux of the left sidewalls of staircase are also investigated, and the measured values in an opened staircase are higher than those in a closed staircase, due to the tilted flame. For the cases in the opened staircases, the time-average total radiant flux and total heat flux at the fully developed fire stage in cases with the 12th window opened keep the highest, because of the longer flame length and higher wind speed induced by the stack effect, while the values in other cases are lower and have no obvious variety regulation. To sum up, the results obtained in this paper may be used for the safety design of the room in the high-rise buildings.

Acknowledgement

This research was supported by the National Basic Research Program of China (973 Program) under Grant No. 2012CB719700 and the Fundamental Research Funds for the Central Universities under Grant No. WK2320000014.

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