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A Study of Internal Fire Whirl in a Vertical Shaft Model with Partially Open Roof

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Abstract

An internal fire whirl (IFW) can be generated readily in a tall vertical shaft model under appropriate ventilation provisions. IFW inside a shaft model with corner gap ventilation and closed roof has been reported earlier. It is demonstrated in this paper by scale modeling experiment that an IFW can also be generated even when the ceiling is partly open for smoke extraction. A shaft model of width 34 cm, length 35 cm and height 145 cm, with a 3.6-cm corner gap to provide ventilation on the side. A 7-cm diameter fuel tray of n-propanol was used. Fire in the shaft model was studied under two scenarios, with front-half covered roof and rear-half covered roof (relative to the position of the gap). Background-oriented Schlieren (BOS) technique was applied to measure the neutral plane height across the corner gap. Thermocouples were used to measure smoke temperature and to counter-check results from the BOS technique. Compared with the closed-roof model, IFW was generated at an earlier time, and fuel burning rate was higher in the partly opened roof scenarios. In addition, the smoke layer was kept at a higher level and had a lower temperature.

Keywords: internal fire whirl; stack effect; neutral plane; Schlieren technique; tall hall fire

1. Introduction

Vertical shafts are found in tall buildings [1-3] for different reasons. An internal fire whirl (IFW) can be generated readily by a fire in a vertical shaft [4-9]. When an IFW occurs, the burning characteristics change, with the flame height increasing significantly. The burning mechanism is very complicated for an IFW. Analytical solutions of the associated aerodynamics are difficult to achieve through theoretical studies. Physical experiments have to be carried out but full-scale burning tests require prohibitive resources. In view of these difficulties and limitations, scale model experiments have become important methods in studying IFW. The heat transfer and air flow can be studied by scale models with appropriate scaling law [10,11].

With rapid growth in economics, many big cities have emerged in the past few decades. There are many big building complexes with a tall atrium to provide better indoor environment such as natural lighting [2,3] as in Figure 1. Fire and smoke spread faster in this kind of architectural feature due to stronger driving forces for smoke movement resulting from stack effect [1,12,13]. Flame swirling was observed while carrying out hot smoke test in an atrium hall with a pyramid shape by Meroney [4].

Figure 1. A typical tall hall in Hong Kong

An IFW was generated in some Taiwanese high-rise buildings as reported earlier using a scale model [14]. The smoke layer interface height relating to the neutral plane height through the opening is an important parameter in relation to evacuation of occupants staying at lower levels and to thermal radiation received by firefighters. Experiments were carried out in a vertical shaft model [14,15] with ventilation provided from the side walls. Flame swirling can be generated in a tall hall with a large volume as in Figure 1. An IFW can occur readily in a tall shaft with a partially opened roof, such as opening a horizontal ceiling vent for smoke control [16]. Scale model experiments in the same shaft model as in [14] were repeated in this paper to study IFW under different roof opening conditions. The burning rate of the fuel was studied under two different scenarios of roof opening of the tall shaft: a front-half covered roof and a rear-half covered roof, to simulate the effect of a ceiling vent for smoke control.

2. Scale Model Experiments

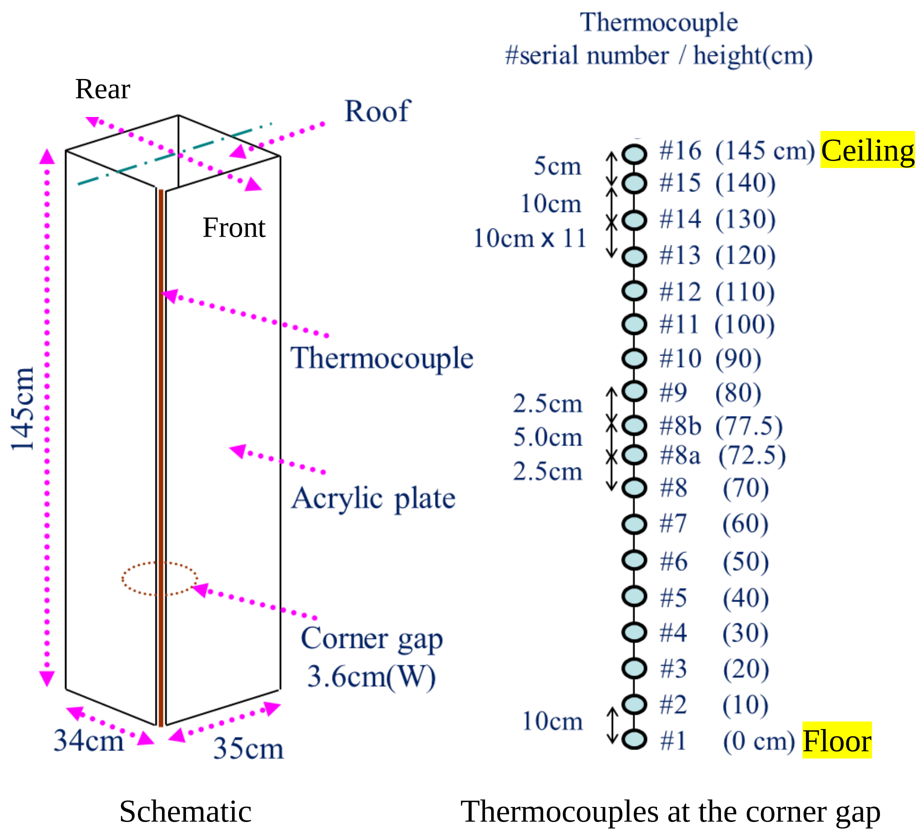
A shaft model of width 34 cm, length 35 cm and 145 cm height, with a 3.6 cm slot on the side constructed earlier was used in this experimental study. Tests were carried out in the model as shown in Figure 2. Transient mass, temperature and images were recorded. Height marks were drawn on the back of the model at 5 cm intervals for estimating the flame height.

Front-half covered : FHC

Rear-half covered: RHC

Photograph

(a) Scenarios



(b) Shaft model

Figure 2. Experimental scenario in the shaft model

Visualizing technology was developed based on refraction of light travelling in different media, including shadowgraph method, Schlieren Photography and optical holography. Background-oriented Schlieren (BOS) [17] is a Schlieren Photography technique applied for studying fluid flow fields. For light travelling through a fluid with motion from a background light source to a digital camera as in Figure 3, the light would be refracted and then deviated from the original path to the sensor denoted by the dotted line with deviation Δh. By comparing the images with and without passing through fluid at the photosensitive sensor, with Particle Image Velocimetry (PIV) image processing technique, Δh can be determined. The flow fields can be measured by BOS using integral effects of the optical light path.

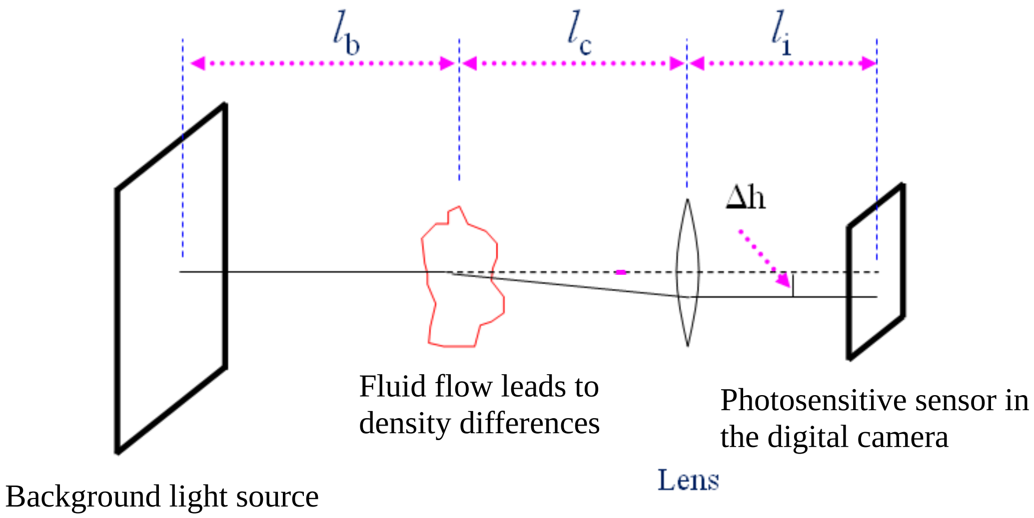


Figure 3. Optical path

As reviewed in the literature [14,15,18], the fluid density ρ is related to the refractive index n through a Gladstone-Dale constant (in m^3/kg) $G(\lambda)$:

$$\frac{n-1}{\rho} = G(\lambda) \tag{1}$$

$G(\lambda)$ for air studied in this paper is expressed by:

$$G(\lambda) = 2.2244 \times 10^{-4}\left[1 + \left(\frac{6.7132 \times 10^{-8}}{\lambda}\right)^2\right] \tag{2}$$

The typical value of $G(\lambda)$ is lying between 0.1 x 10^{-3} and 1.5 x 10^{-3}.

The deviation distance Δh (in m) can be expressed in terms of the focal length of the lens f (in m) and the wavelength of light λ (in m) through optical path lengths l_b, l_c and h (all in m):

$$\Delta h = \frac{1}{n}\left(\frac{l_b f}{l_b + l_c - f}\right)\int_{l_b-\Delta l_b}^{l_b+\Delta l_b} \frac{\partial n}{\partial r} dl \tag{3}$$

As shown in Figure 4, hot gas would move out from the upper part of an opening and ambient cool air would come in from the lower part of the opening in a room fire. Those hot gas and cool air would have different refractive indices due to their temperature differences. BOS technique can then be applied to determine the boundary location of hot gases and cool air, which is in fact the neutral plane position of the opening in a compartment fire [14,15].

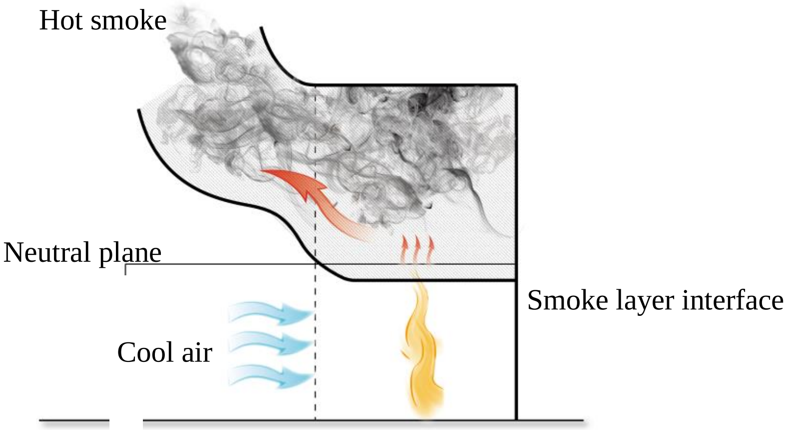


Figure 4. Neutral plane and smoke layer interface height

Air exchange flow pattern across the corner gap of the shaft model could be determined clearly using the BOS technique [17]. The location of zero air flow at the gap [14] could be used to define the neutral plane height, which is in general slightly different from the smoke layer interface height [19-22] within the room model, as shown in Figure 4.

Location of the neutral plane height across the corner gap [23,24] (and hence the smoke layer interface [14] inside the model for some cases) determined was subsequently compared with the air temperature variation measured using thermocouples. Details of how the BOS technique simplifies the visualization process by eliminating the high cost of using lasers, mirrors and knife blades were outlined earlier in the literature [14].

A pool fire of 7 cm diameter was placed in the middle of the model. 20 ml of n-propanol was put in the fuel tray to provide an adequate burning time. An electronic scale was used to record the transient mass of the fuel. n-propanol was selected because the amount of heat generated in its burning process was appropriate, without producing black smoke that would interfere with the recording of the dynamic images. The setting was such that the fuel mass would be recorded every second.

The scenario of burning the pool fire in free space is labelled as FS.

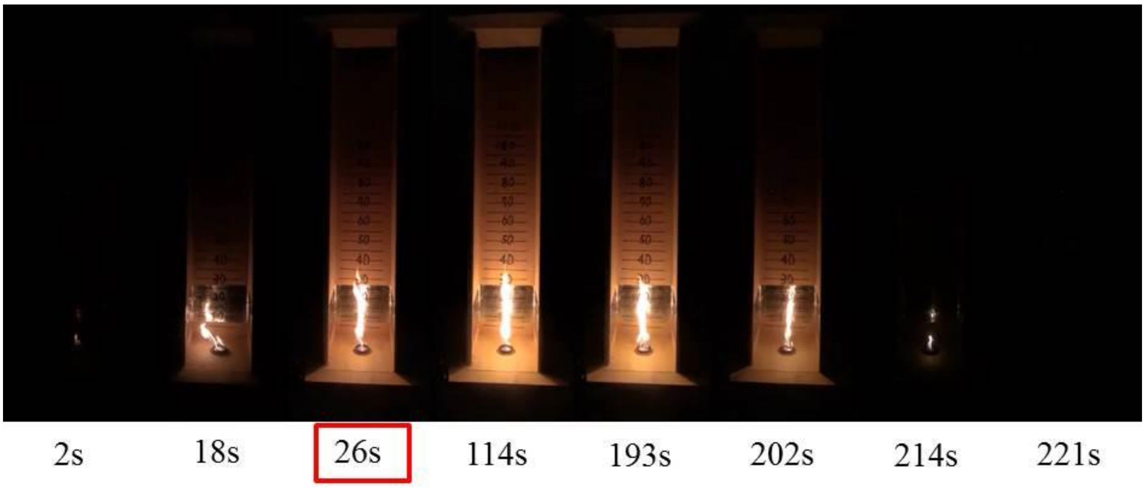
Two scenarios of burning the pool fire in the model with different roof arrangements as shown in Figure 2 were carried out:

- Scenario FHC: Front-half covered
- Scenario RHC: Rear-half covered

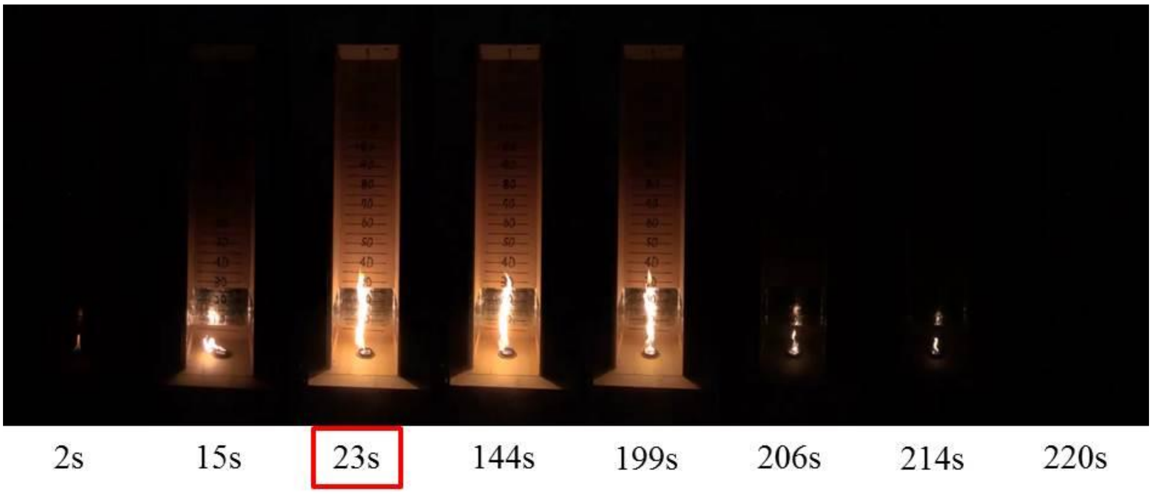
Results are also compared with those reported earlier with the roof closed.

3. Creation of Internal Fire Whirls

Eight pictures were taken on the transient flame shapes for each of the scenario FHC and RHC as shown in Figure 5. The first two pictures are on starting the pool fire. The third picture was taken when an IFW was created. The sixth picture was taken when the flame began to fade and the last picture was when the fire extinguished. The burning times of the fuel were 221 s for FHC and 220 s for RHC.



(a) Scenario FHC



(b) Scenario RHC

Figure 5. Internal fire whirl

The fuel in the 7-cm diameter tray was first burnt in free space. No swirling flame was generated. The flame height was rather steady, with an average value of 18 cm over the burning duration of 369 s.

In the shaft model, swirling flame was not observed initially, but was generated after some time when burning started, taking about 26 s for FHC and 23 s for RHC. The opening position of the half-covered roof scenario did not affect the time to create an IFW. The IFW created lasted for some time before it died out. The flame heights increased and decreased with time during the burning period. An average value of 40 cm and a maximum value of 60 cm for the whirling flame height were recorded for both scenarios.

Air required for burning was supplied through the corner gap. On the other hand, the hot air current had to flow out from this same gap if the roof of the model was completely covered. A hot smoke layer was formed as illustrated in Figure 3.

With an IFW for scenarios FHC and RHC, the average flame height increased from 18 cm for FS (without an IFW) to 40 cm. The maximum height of the IFW was 60 cm. Combustible items placed adjacent to the IFW can be ignited to give more hazardous consequences.

The mass loss curves of the fuel in the three scenarios FS, FHC and RHC are shown in Figure 6. There is not much difference between scenarios FHC and RHC as shown in the figure. However, the mass loss rates for FHC and RHC are much faster than FS due to stack effect resulted from enclosing part of the roof.

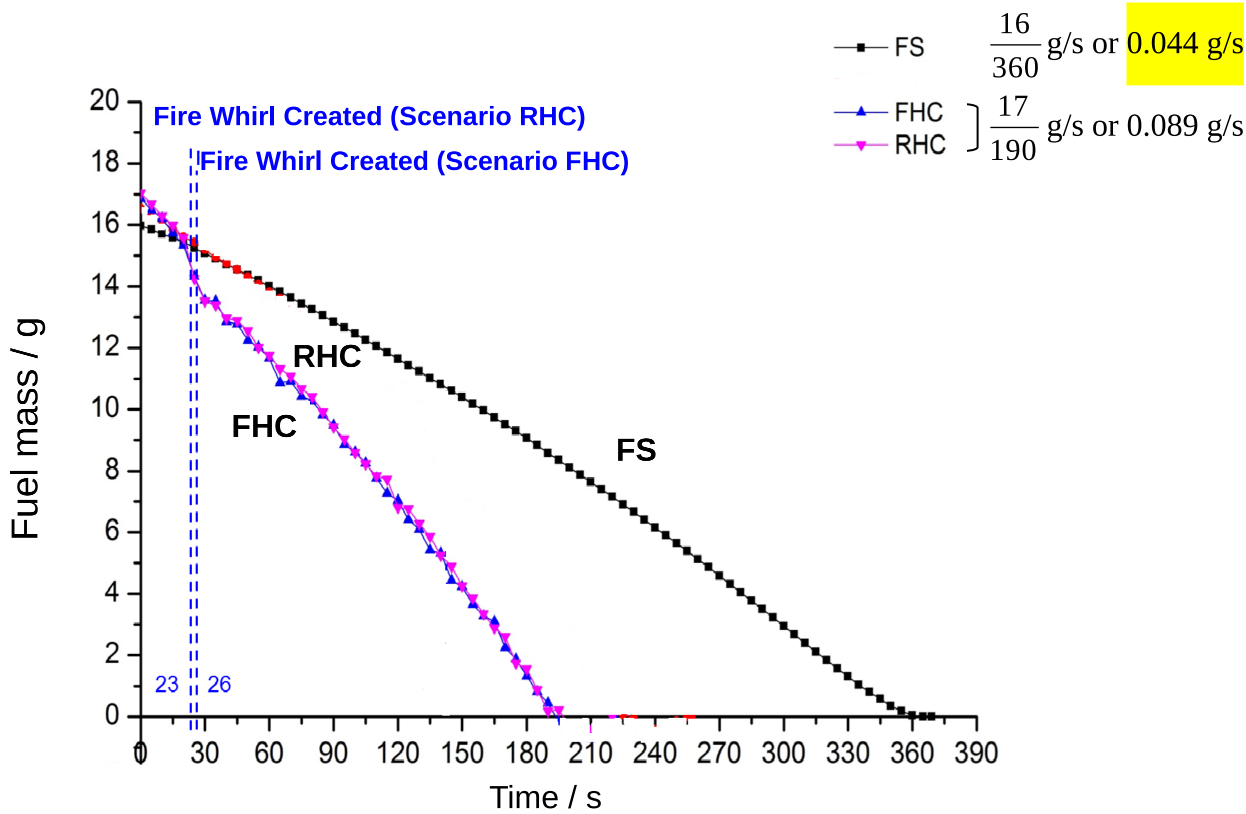


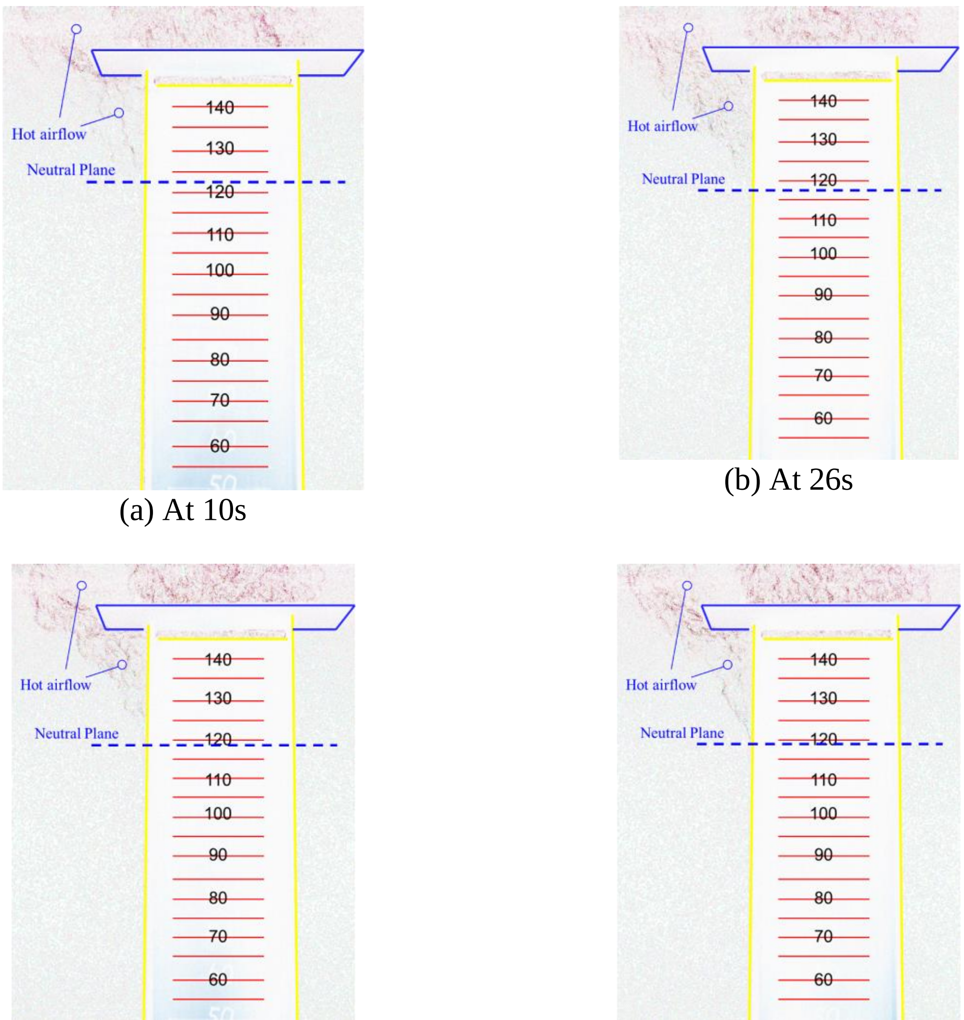
Figure 6. The variation of fuel mass

The mass loss rates increased after the formation of an IFW, giving a much shorter burning duration as compared with the case with whirling. Duration of the pool fire for scenario FS was 369 s, about 1.89 times that for scenarios FHC and RHC. The fuel mass loss rate was steady for scenario FS, with a mass loss rate of 0.044 g/s.

The mass loss rate increased to 0.084 g/s for scenario FHC and RHC once there was an IFW. The values are much higher than pool fire without a fire whirl.

4. Neutral Plane Heights

The outflow of the hot air from the corner gap of the shaft model was recorded using the BOS technique in this study. The hot air flow for scenarios FHC and RHC was illustrated in Figure 7 and Figure 8, respectively.



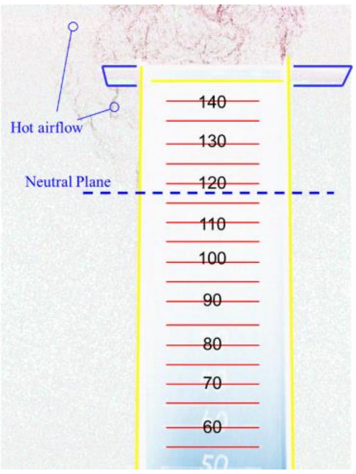
(a) At 10s

(b) At 26s

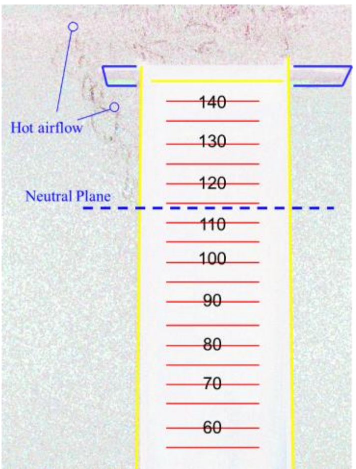
(c) At 46s

(d) At 86s

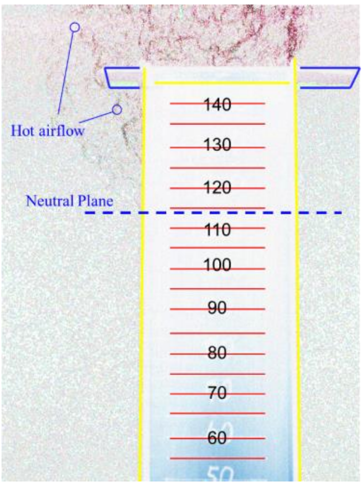
Figure 7. Flow phenomena in BOS for Scenario FHC



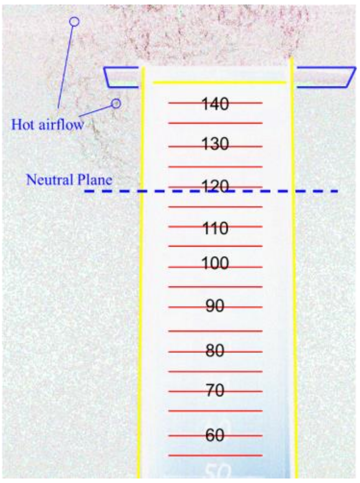
(a) At 10s



(b) At 23s



(c) At 43s



(d) At 83s

Figure 8. Flow phenomena in BOS for Scenario RHC

Figure 7 shows that the neutral plane height was located at about 122 cm after 10 s of burning in scenario FHC, dropped to about 118 cm when an IFW was generated at 26 s, and then remained at this height up to 86 s.

Figure 8 shows that the hot airflow and neutral plane height for scenario RHC were similar to scenario FHC.

In the case with the roof closed as studied before [14], IFW was generated at about 140 s at vertical place 65 cm after rising slightly to 70 cm before the fuel was burnt out at 180 s.

5. Air Temperature Measured

Air temperature changes at the corner gap in each scenario were measured. Air temperature distribution was analyzed at the following time instants:

- 10 s after burning began
- the moment when the fire whirl was formed
- 20 s after the fire whirl was formed
- 40 s after the fire whirl was formed

In scenario FHC, the maximum air temperature inside the hot air layer measured rose from 34°C at 10 s to 49°C at 26 s. At 46 s, the maximum air temperature inside the hot air layer increased to 66°C at 122.5 cm as in Figure 9, which remained unchanged at 181 s.

In scenario RHC, the maximum air temperature inside the hot air layer rose from 34°C at 10 s to 36°C at 26 s. At 43 s, the maximum air temperature inside the hot air layer increased to 55°C at 122.5 cm. At 83 s, the maximum temperature reached 55°C.

A summary of the results on smoke layer temperature and neutral plane height (same as the smoke layer interface height in this study) is shown in Figure 9. The maximum smoke temperature in scenario RHC was slightly lower than that of scenario FHC. Perhaps, a larger amount of hot smoke flowed out of the gap when the roof was covered at the front-half. Temperature decreased significantly and the height of the neutral plane increased accordingly, which were actually beneficial to the people on the lower floors.

As reported earlier in the closed roof case, the maximum temperature was 121°C. Therefore, closing the roof would trap heat inside the shaft model to give a much higher temperature.

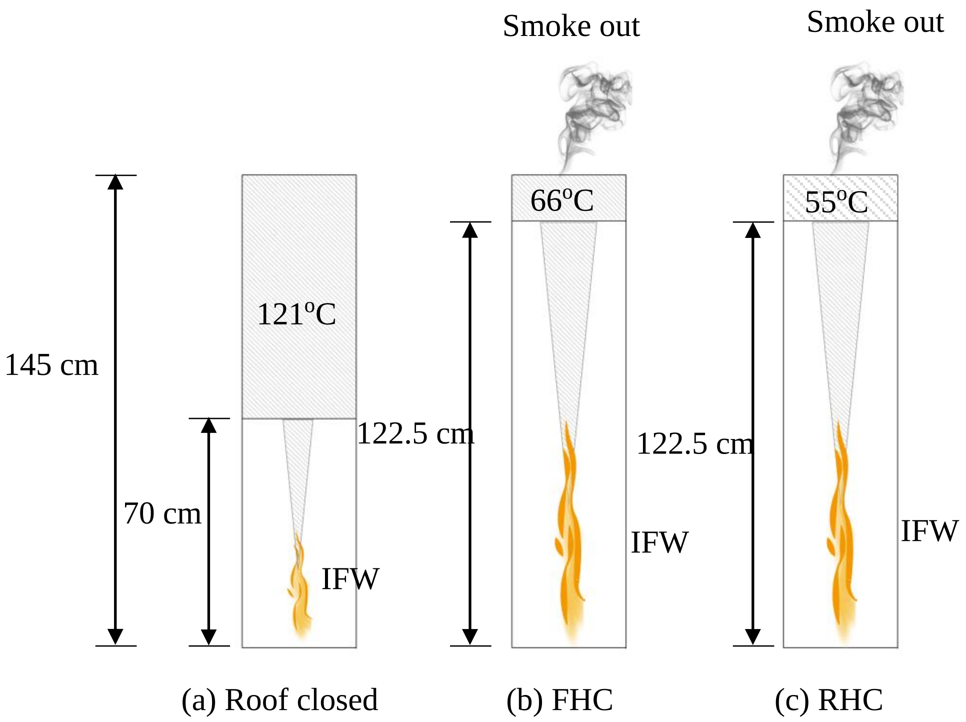


Figure 9. Summary of results

6. Conclusions

Many tall halls are constructed in big complexes for different purposes. An IFW can be generated in the vertical space [2,3] in high-rise buildings, particularly those with green design [25], under certain ventilation conditions. An IFW in such cases would give very hazardous environment. The flame swirling would ignite nearby combustibles. The burning rate is faster to give higher heat release rate and hotter smoke. The characteristics of an IFW, such as flame height, neutral plane height, smoke temperature, and heat release rate are closely related to the ventilation condition. In this study, the effect of the opening of the roof of a tall hall was investigated by using a scale model coupled with the BOS technique. As compared to a closed-roof model of the same configuration, it was observed that with a half-closed roof model,

(i) the smoke temperature was reduced from 121^{o}C for the close-roof model to 55^{o}C for the rear-half covered model;
(ii) the thickness of the smoke layer was significantly reduced in the half-closed roof.

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