Influence of Stairwell Ventilation State on Fire Behavior and Smoke Temperature Distribution in a Full-scale High-rise Building

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Abstract. In this study, a set of experiments were carried out in a 21-story full-scale building varying stairwell ventilation state to investigate the fire behavior and smoke temperature distribution in the stairwell. Results demonstrate that the ventilation state of top vents has a great influence on the fire behavior and smoke temperature distribution than the bottom vents. The flame inclines to the stairwell with top vents open during the steady stage, while with top vents closed, it just tilts slightly to the side wall. The mass loss rates and temperature attenuations with top vents closed are larger than those with top vents open. In addition, the open of bottom vents can cause a reduction in the smoke temperature. These unique full-scale experiments provide crucial experimental data that help the design of safer smoke ventilation systems for stairwells in a high-rise building.

1. Introduction

In recent years, fire accidents in high-rise buildings have occurred more frequently and caused several casualties and significant loss of property [1]. There are many vertical shafts in high-rise buildings, such as stairwells, elevator shafts, ventilation shafts, and cable shafts. In the event of a fire, these vertical shafts become primary passages for smoke to spread to other floors [2]. Previous studies have found that the smoke movement is mainly driven by stack effect and turbulent mixing [3, 4]. Stack effect is a phenomenon caused by the pressure difference between the gas inside the stairwell and the air outside of the stairwell [5], while turbulent mixing is a phenomenon connected with Rayleigh-Taylor instability [4].

A number of studies have been conducted to investigate the fire behavior and temperature distribution in a stairwell. Ji et al. [6-7] conducted a series of small-scale experiments to study the effect of the opening height on the smoke movement and temperature distribution in the stairwell, and the flame characteristics in the fire room. He et al. [8] conducted a series of full-scale experiments to study the smoke movement in a stairwell and found the temperature distribution can be divided into a lower and an upper region by the upper opening.

The fire source in the previous studies were located on the first floor. However, in a real fire accident, the fire source could be located on any floor of high-rise buildings. In this case, the state of vents on the lower and upper floors would affect stack effect in the stairwell, which further affects the fire behavior and smoke temperature distribution. Therefore, to study the influence of the stairwell
ventilation state on the fire behavior and smoke temperature distribution in high-rise buildings, a set of experiments were conducted in a full-scale stairwell.

2. Full-scale experiments
Four full-scale experiments were conducted in a 21-story stairwell of an office building. Figure 1 shows the layout of the stairwell and experimental setup. The overall height of the stairwell is 89.7 m, where the first floor is 6 m high, the second and third floors are 4.5 m high, the 21st floor is 8.4 m high, and all other floors are 3.9 m high. The cross-section of the stairwell and lobby are 6.5 m × 2.7 m and 4 m × 2.7 m, respectively. Two doors with a size of 2.1 m high by 1.4 m wide connected the stairwell, lobby and corridor [8].

Ethanol was selected as the fuel for the fire source and the fuel pan used was rectangular with dimensions of 0.585 m wide, 0.13 m high, and 0.841 m long. The fire source was located on the lobby of the 5th floor and 80 cm away from the stairwell door as shown in figure 1. In each test, the mass loss data of pool fire was measured in real-time by using an electronic balance with a precision of 0.2 g and a sampling interval of 0.1 s. Two digital videos were set in the experiment to record the experimental phenomena on the 5th floor. One was set at the left side of the lobby, the other was set at an angle of 30 degrees to the lobby door. The temperatures of hot smoke at the centreline of the stairwell were measured by seventeen fine-wire K-type thermocouples (1mm in diameter) as shown in figure 1.

![Figure 1. Schematic of the 21-story full-scale stairwell.](image-url)
All experimental conditions are summarized in Table 1. During the experiments, the doors on the 5th floor were kept open to allow the entrainment of fresh air and the doors on the first floor and 21th floor could be open or closed for different stairwell ventilation states. The external temperature was recorded via a mercury thermometer during each experiment, as 29-32 °C. Each experiment was repeated twice and results presented good repeatability with measurement uncertainties less than 5%.

| Test No. | Pool position | Ventilation state |
|---------|---------------|-------------------|
| A       | 5F            | 21F Doors Open, 1F Doors Closed |
| B       | 5F            | 21F Doors Open, 1F Doors Open |
| C       | 5F            | 21F Doors Closed, 1F Doors Closed |
| D       | 5F            | 21F Doors Closed, 1F Doors Open |

3. Results and discussion

3.1. Fire behavior

The flame inclination may ignite distant combustibles and enhance the probability of fire spreading in the horizontal direction. Observing the videos from the experiments, it can be seen that the ventilation state of top vents (21F doors) has a great influence on the fire behavior than the bottom vents (1F doors). Different perspectives of a set of flame shapes over time in all cases are shown in figure 2.

Figure 2(a) shows the case with only 21F doors open, and it can be seen that at the early stage, the flame is relatively stable and does not tilt towards any directions. With the development of combustion process, hot smoke flows into the stairwell, inducing temperature rise in the stairwell and stack effect. At about 100s, the flame begins to incline to the direction of the stairwell due to the supplement
airflow through the lobby door. While in the case B (doors on 1F and 21F are open), it can be found that the flame would incline to the lobby door at the initial stage by the airflow through the stairwell door from the lower region below the fire floor, and the time for the flame starting to tilt to the stairwell is later than the case with only 21F doors open.

Figure 2(c) and (d) shows the cases that the doors on 21F are closed, in this situation, the smoke movement in the stairwell is mainly driven by turbulent mixing and the location of neutral plane is at the lobby door of the fire floor. The fire induced plume not only flows into the stairwell, but also flows out through the upper region of the lobby door above the neutral plane and fresh air flows into the lobby through the lower region below the neutral plane, inducing that the flame inclines slightly to the side wall at the steady stage.

3.2. Mass loss rate

The mass loss rates in different cases are shown in figure 3. Blinov and Khudiakov [9] pointed that the burning rate of pool fire was dominated by the heat feedback from the oil pans and flame to the fuel, while the magnitude of the heat feedback was significantly related to the flame shape of pool fire. In the cases with 21F doors open, the flame shapes at the steady stage are almost the same and inclines to the stairwell due to stack effect, inducing the same heat feedback received from flame. Therefore, the mass loss rates in the case A and case B are almost the same as shown in figure 3.

While in the cases with 21F doors closed, the flame just slightly inclines to the side wall, resulting in larger heat feedback than the cases with 21F doors open, hence the mass loss rates in the case C and case D are larger. It also can be seen from the figure 3 that the ventilation state of 1F doors has a great impact on the mass loss rate when the 21F doors are closed and the mass loss rate in the case D is larger than that in the case C.

3.3. Smoke temperature distribution in the stairwell

The vertical temperature distributions along the centreline of the stairwell are shown in figure 4. It can be seen that the temperature decreases as the height increases. To clarify the trend of the temperature distribution in the stairwell, the decay of temperature is fitted by an exponential function as follows [10]

\[ \Delta T = T_H - T_i = Ae^{-\beta H} \]

\[ \beta = \frac{k}{m} \]

\[ (1) \]

\[ (2) \]
where $T_H$ is the temperature at the vertical height $H$; $T_0$ is the temperature of the ambient air; $\beta$ is the temperature attenuation coefficient; $m_s$ is the mass flow rate of smoke flowing into the stairwell, and $k$ is a coefficient determined by the initial conditions related to the stairwell size.

On the basis, an obvious feature can be observed that temperature attenuations are greater in the cases with 21F doors closed for larger values of the coefficient $\beta$. When doors on 21F are closed, the smoke movement is induced by turbulent mixing with smaller mass magnitude and lower upward velocity, resulting in larger contact area and longer contact time between hot smoke and stairwell, thus the heat loss is greater in comparison with the cases when doors on 21F are open. From figure 4, it also can be found that the open of doors on 1F can reduce smoke temperature in the stairwell.

4. Conclusion
In this paper, after a series of experimental study, the following conclusions can be got.

(1) The ventilation state of top vents has a great influence on the fire behavior than the bottom vents. The flame inclines to the stairwell with top vents open during the steady stage due to the supplement airflow through the lobby door under stack effect. While with top vents closed, it just inclines slightly to the side wall.

(2) When top vents are open, whether the bottom vents are open or closed, the mass loss rates have no difference. However, when top vents are closed, the mass loss rates are obviously larger with bottom vents open. The mass loss rates with top vents open are larger than those with top vents closed.

(3) The temperature attenuations with top vents closed are greater. It is because that when top vents are closed, the smoke movement is induced by turbulent mixing with smaller mass magnitude and lower upward velocity, resulting in larger contact area and longer contact time between hot smoke and stairwell, thus the heat loss is greater in comparison with top vents open. In addition, the open of bottom vents can reduce smoke temperature in the stairwell.

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