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Reduced-scale experimental and numerical investigation on the energy and smoke control performance of natural ventilation systems in a high-rise atrium

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Abstract. Natural ventilation (NV) is an effective energy-saving strategy to remove the excessive heat in high-rise atria. The traditional NV system in high-rise atria has inlet openings at the bottom and outlet openings at the top. However, this traditional system may bring fire safety concerns due to the rapid spread of smoke during an atrium fire. To remove the fire safety concern, a new NV system was proposed in this study. This new system applies a segmentation slab to divide the high-rise atrium into upper and lower parts, which can limit the smoke movement. A ventilation shaft is installed to maintain the NV rate and extract smoke. To investigate the energy and smoke control performance of the new and traditional NV systems, a 1:20 small-scale experimental model and CFD numerical model were built. The results indicate that the new NV system with the shaft and segmentation can remove more heat than the traditional NV system. Furthermore, the new NV system can simplify the mechanical smoke exhaust system and improve the smoke control performance, e.g., requires a lower volumetric flow rate and maintains a thinner smoke layer.

1 Introduction

Reducing the cooling energy consumption in high-rise buildings is critical. On the one hand, the huge space cooling demand is becoming a challenge on electricity systems. The space cooling energy consumption has tripled in the world from 1990 to 2016 [1]. On the other hand, the number of high-rise buildings is increasing, due to population growth and limited land in cities. It was reported that the cities with over 100 high-rise buildings reached 142 in 2019 [2].

Among many technologies (e.g., advanced glazing and shading), natural ventilation (NV) is an effective energy saving strategy in high-rise buildings, i.e., ventilative cooling. The previous study showed that the high-rise building can save up to 25%~86% of the electricity consumption if the NV is applied [3,4]. The driven forces of NV include wind and buoyancy. The buoyancy force is generated by the pressure difference when the indoor temperature is greater than the outdoor temperature. Compared with using wind-driven NV, one of the advantages of high-rise buildings is to utilize the buoyancy-driven NV due to their large vertical space.

Atria provide impressive aesthetic space and increases socialization and interactions, which is the appropriate architectural component to employ buoyancy-driven NV [5,6]. The traditional NV system in high-rise atria has inlet openings at the bottom and outlet openings at the top. The air enters the atrium at the bottom and then exhausts to the outside at the top of the atrium.

However, when a fire occurs in high-rise atria, the smoke movement is difficult to control. The high-rise atrium will become a smoke path. Toxic smoke will move vertically and reach the upper part of the atrium, damaging the building and threatening the occupants [7,8]. Therefore, the atrium height usually is limited by the segmentation slab, which damages the potential of NV in turn. It was reported that several high-rise atria were divided into smaller sub-atria due to fire safety. For example, the atrium in Commerzbank (56-story) in Germany was built into 12-story-high sub-atria [9]. The atrium in Concordia EV building was divided into five sub-atria (three floors each segment) [10].

To mitigate the conflict between the fire safety concern and energy performance in the atrium NV system, a new NV system is proposed. This new NV system consists of two components: segmentation slab and ventilation shaft. The segmentation slab is to divide the atrium into different parts, which limits the height of the atrium. The ventilation shaft is to maintain the NV rate and extract smoke. This paper aims to evaluate the ventilation and smoke control performance of this new NV system. A 1:20 small-scale experimental model and a CFD model were developed. The experimental model is used to evaluate the ventilation performance, which demonstrates the temperature distribution in the atrium, ventilation rate, and heat removed by ventilation. The CFD numerical model is used to examine the smoke control performance, which shows the smoke layer heights.

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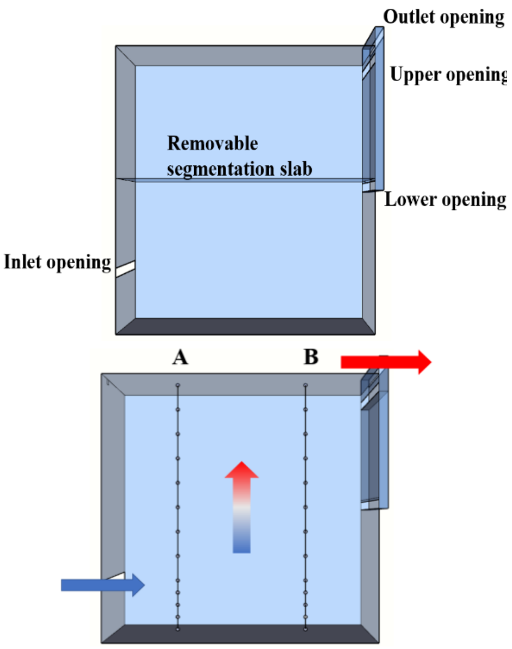
2 Methodology

2.1 Experimental settings

To compare the ventilation performance of the new NV and the traditional NV systems, a 1:20 small-scale acrylic model, 1.5 m (L) * 0.6 m (W) * 1.5 m (H) was built, which is shown in Fig.1. To switch the NV systems between the novel and traditional type, a removable segmentation slab is placed at 0.8 m height. A ventilation shaft is installed at the side of the model.

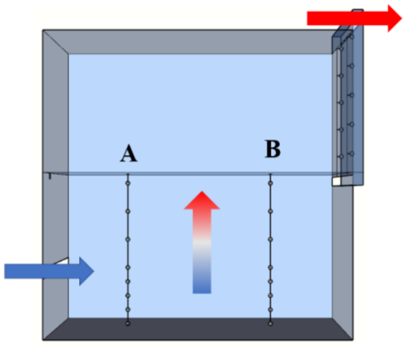
To simulate the internal cooling load and generate the buoyancy forces, a 250W heater is positioned at the centre of the atrium bottom, which is 0.6 m (L) * 0.2 m (W). To measure the temperature distribution inside the atrium, the thermocouples with the accuracy of ±0.3 ℃ were installed at A, B position and shaft, as shown in Fig.1. (b) and (c). At the inlet and outlet opening, two anemometers with the accuracy of ± 0.1 m/s were installed to measure the air velocity.

For the traditional NV system as Fig.1. (b) shows, the outside air flows into the atrium from the inlet opening (0.3 m height). Due to buoyancy, the air warms up and passes through the upper opening (1.5 m height), and finally exhausts at the outlet opening (1.6 m height). For the new NV system, as Fig.1. (c) shows, the outside air flows into the atrium from the inlet opening (0.3 m height). Due to buoyancy, the air warms up and passes through the lower opening (0.8 m height), and finally exhausts at the outlet opening (1.6 m height). All these openings are 0.03 m^2.



(a)

(b)



(c)

Fig. 1. Outline of the experimental model and arrangement of measurements (a) overview of the experimental model, (b) airflow direction and arrangement of thermocouples in the traditional natural ventilation system, and (c) airflow direction and arrangement of the thermocouples in the novel natural ventilation system.

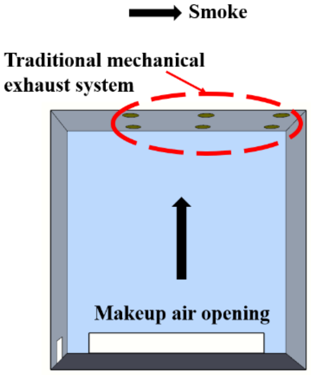
2.2 Numerical settings

To compare the smoke control performance of the new NV system and traditional NV systems, two small-scale CFD numerical simulation models were built in Fire Dynamic Simulator (FDS), as Fig.2. shows.

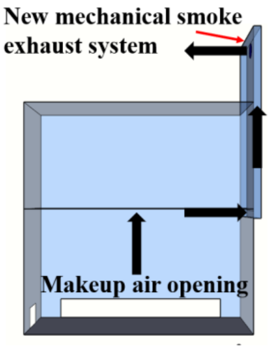
According to the reference, in the atrium with limited fuel, the heat release rate (HRR) can be assumed as 2MW [11]. Based on Froude scaling (1:20), a 0.1 m * 0.1 m fire source with a 1.1 kW fire was simulated at the centre of the atrium bottom. Considering the limitation of the makeup air velocity (1.02 m/s), the makeup air openings on the two sides of the atrium were added (0.17 m^2). In this simulation, based on the reasonable ratio of characteristic diameter to grid size (i.e., the grid size should not be larger than 0.015 m) [12], the 0.013 m grid size was used.

The first model is used to show the performance of the traditional mechanical exhaust system. According to the ASHRAE handbook [13], this system has six exhaust inlets, and each inlet has a 13.4 L/s flow rate (81 L/s in total). This exhaust flow rate aims to maintain a minimum smoke layer of 20% floor-to-ceiling height when a 1.1 kW fire occurs. The second case is the new mechanical exhaust system. According to the ASHRAE handbook [13], due to the reduction of the atrium height, the required volumetric flow rate is only 32 L/s for a same 1.1 kW fire and smoke layer depth.

For these two cases, the smoke layer heights were measured at A and B positions (see Fig.1.).



(a)



(b)

Fig. 2. Exhaust inlets for two mechanical smoke exhaust systems and smoke exhaust path (a) traditional mechanical exhaust system and (b) new mechanical smoke exhaust system.

3 Results and discussion

3.1 Ventilation performance

Fig.3. presents the measured temperature distribution at A, B positions and shaft for the traditional and new NV systems with the surrounding temperature at around 21.5 ℃ in the experiments. It should be noted that the temperature data over 0.8 m height in New-B & shaft are the temperature distribution in the shaft. Fig.3. shows that the temperatures are very close at the bottom for the two NV systems, which means that the new NV system can maintain the temperature of the occupied space as low as the traditional NV system. For example, the temperature differences between two NV systems are 1.1℃ and 0.5 ℃ at the bottom of A and B positions.

To further investigate the ventilation performance of two NV systems, Fig. 4 presents the measured mass flow rate and calculated heat transfer by ventilation. It was found that compared with the traditional NV system, the mass flow rate and the heat removed by ventilation in the new NV system increase 22% and 21% respectively. These results that the new NV system can better utilize the buoyancy force and ventilation to remove heat.

However, it can be found that the temperature near the segmentation slab in the new NV system is clearly higher than the temperature at the same height in the traditional NV system. This difference may be caused by the heat transfer through the wall and airflow pattern, which requires further investigation in future.

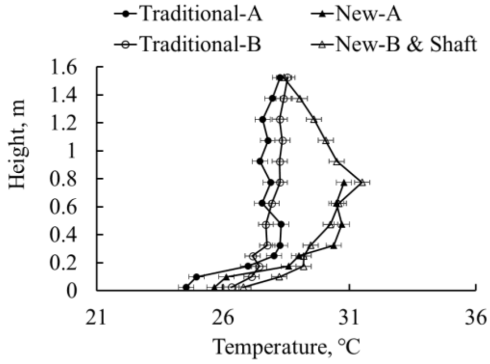


Fig. 3. Temperature distribution in the experiments.

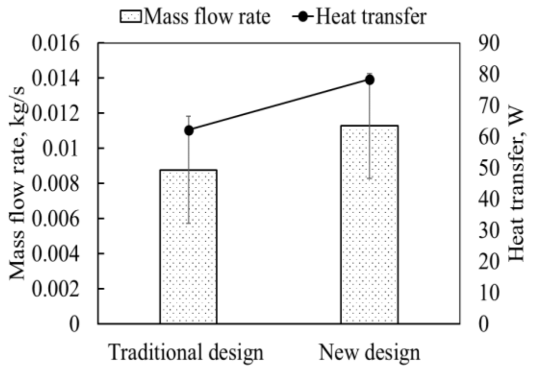
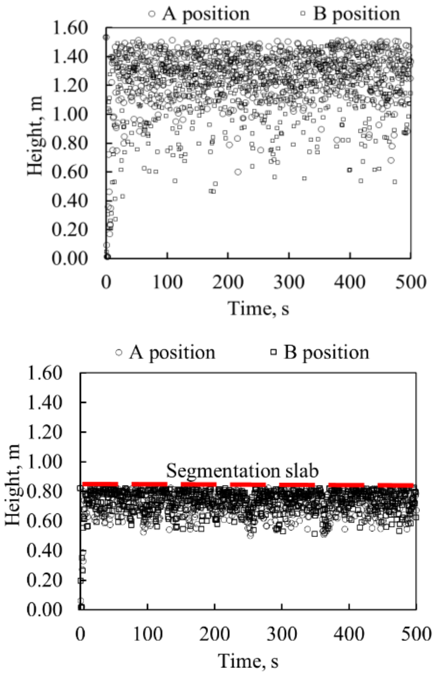


Fig. 4. Measured mass flow rates and calculated heat transfer by ventilation in the experiments.

3.2 Smoke control performance

Fig. 5. presents the smoke layer heights at A and B positions in the traditional and new designs. These results show that the atrium with the new NV system has a better smoke control performance than the atrium with the traditional NV system. Firstly, compared with the atrium with the traditional NV system, the atrium with the new NV system has a thinner smoke layer. For example, Fig. 5. (a) shows that the smoke layer mainly spans from 0.9 m to 1.5 m, i.e., the smoke layer depth is 0.6 m. However, Fig. 5. (b) shows that the smoke layer concentrates on the heights from 0.3 m to 0.8 m, i.e., the smoke layer depth is only 0.3 m. Secondly, as mentioned in section 2.2, the mechanical exhaust flow rate in the atrium with the new NV system (32 L/s) is only 40% of that in the atrium with the traditional NV system (81 L/s). However, in this study, only one heat release rate and exhaust flow rate were examined. More fire conditions and mechanical systems should be investigated in future.



(a)

(b)

Fig. 5. Smoke layer height at A and B positions in (a) traditional design and (b) new design.

4 Conclusion

This study proposes a new NV system. The ventilation and smoke control performances of this new ventilation system were evaluated by small-scale experiments and numerical simulations. For NV performance, the atrium with the new NV system can have a similar temperature distribution at the atrium bottom (i.e., occupied space), but a larger ventilation rate than the traditional NV system. The heat removed by ventilation is larger in the new NV system than in the traditional NV system (i.e., better ventilative cooling). For smoke control performance, the new ventilation system requires a lower volumetric flow rate for smoke exhaust than the traditional design, but the smoke layer in the new design (around 0.3 m) is thinner than in the traditional design (around 0.6 m). These two performances indicate that this new system can promote the NV application in high-rise atria but mitigate the smoke control problem.

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