How a Natural Ventilation Shaft Affects Smoke Layer Descent in Room Fires

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Abstract

In this study, full-scale experiments were conducted to observe the influence of a natural ventilation shaft on smoke layer descent in room fires. An oil pan with a heat release rate of 50 kW was ignited in a model space to generate fire smoke for the observation of smoke layer descent and flow conditions under various natural ventilation conditions. It is found that when there is no natural ventilation shaft available in a room that is on fire, the height of the descending smoke layer in the fire room has nothing to do with whether the natural ventilation shaft has been set up or not in the adjacent non-fire room. However, when a natural ventilation shaft has been set up in the fire room, it is able to effectively raise the smoke layer height.

Keywords: natural ventilation; fire; smoke; Green Building

1. Introduction

As natural ventilation is advantageous in reducing the energy consumption of buildings and in maintaining adequate indoor air quality (IAQ), it is a key component of Green Building design. Skillful natural ventilation design can direct the airflow route indoors, and can greatly influence the spread of fire and high temperature gas as well as smoke flow in a building that is on fire. Therefore, the issue of the interaction between and influence of natural ventilation design and fire safety is worthy of advanced study.

1.1 Natural ventilation design

Airflow between the interior and exterior of a building through its openings can be said to demonstrate free convection or forced convection. The driving force of free convection is gravitational force, i.e., the temperature difference between the air indoors and the air outdoors (stack effect or buoyancy effect). In contrast, the driving force of forced convection comes from the pressure difference induced by outdoor wind movement or a mechanical apparatus. Natural ventilation refers, in general, to the airflow driven by natural forces. Therefore, natural ventilation includes both the above-mentioned wind force and buoyancy.

Many building physics textbooks mention the "Wisdom of the natural ventilation design of animal nests": if airflow is "sucked in" at a lower point and guided through an indoor duct, then finally merges with outdoor airflow at a higher point in extraction, the result is an effective natural ventilation route. According to this theory, natural ventilation design in buildings simulates the wisdom of animals in constructing nests on the basis of "Bionics".

During the process of architectural design, designers may utilize a wind scoop (cowl) and airflow pathway design to introduce outdoor air into the interior, which ensures effective air circulation indoors. Wind scoops can be pre-manufactured and installed externally, or aspects of the form of the building can be designed to function as a wind scoop, at the same time contributing to the creation of different architectural styles. A wind tower (cowl) takes advantage of the partial negative pressure created when wind passes through the wind tower openings or if the wind tower rotates. The indoor air can be exhausted with the proper combination of this partial negative pressure and airflow pathway.

Except for the consideration of outdoor wind, the application and compliance of thermal buoyancy is another critical key in designing natural ventilation. (Mistriotis et al., 1997) pointed out the following: when the outdoor wind speed $V_e > 2$ m/s, the wind force influences natural ventilation much more than thermal buoyancy, which can be ignored. While $2$ m/s > $V_e > 0.5$ m/s, the wind force is still greater than the thermal buoyancy, but the thermal buoyancy cannot be ignored. When $V_e < 0.5$ m/s, the influence of thermal buoyancy becomes significant.

Based on the average outdoor wind speed of 1.2-4.0 m/s in the Taiwan area, it is necessary to consider the combined influence of the effect of the forces of wind and thermal buoyancy on natural ventilation. In
addition, the indoor heat source or a heated façade by solar heat gain will heat the adjacent air, which rises to the higher parts of buildings due to the thermal buoyancy effect. At this time, if there is an opening at the top, the heated air will leave the construction and form an effective natural ventilation route. Meanwhile, two streams of natural ventilation (via outdoor wind and thermal buoyancy) should be able to complement each other without interference so as to promote the combined effectiveness.

1.2 Considering fire safety when designing natural ventilation

When considering airflow space, if a building has good natural ventilation it could mean that it has a certain vertical and horizontal interconnected puncture. However, fire safety is achieved by passive building construction in fireproof protection, an active firefighting system and fire-safety management. Thus, natural ventilation design has always conflicted with fire safety design norms (particularly the passive building construction in fireproof protection) or regulations. After all, natural ventilation seeks the utilization of vertical and horizontal fireproof compartments in preventing fire spreading with respect to the issue of building fire safety.

(Chow et al., 2005) noted that in Hong Kong, certain Green Buildings cannot meet the requirements of fire safety (regulations), such as complex indoor virtual (vertical) space, double layer-building facade, too much natural ventilation (route and volume) and overly high atriums (Chow and Chow, 2003). With respect to these conflicts (Green Building Design vs. Fire Safety), (Chow, 2003) suggested taking a fire engineering approach (similar to performance-based design) to balance both.

(Short et al., 2006) showed that a building designed with natural ventilation strategies would require increased costs to install fire doors or dampers so as to fulfill the compartment requirements of fire safety regulations. These extra facilities will influence the function of daily natural ventilation. Using mechanical ventilation equipment to promote the expelling of smoke would, in addition to increasing costs, reduce the possibility of adopting natural ventilation design via the concept of VE (Value Engineering). In constructional planning, due to the consideration of fire safety regulations and budget, natural ventilation design has always been rejected due to the issues of risk management and value engineering. Hence, the development of natural ventilation in theoretical and practical aspects should be combined with higher reliability so that it will become a workable solution for designers.

2. Research Method

2.1 Model space development and design

Many critical key points have been encountered in this study, and one of them is the determination of the investigated model space. Natural ventilation design can be categorized into various considerations, such as horizontal and vertical airflow types for integrated or individual spaces, single houses, apartments, or mansions with lifts. All of these aspects are worthy of investigation. Our study will focus on the following premise to determine the investigated model space: ventilation style with specific horizontal and vertical design, multi-space connection, minimum ventilation rate in regulations, and simplified space.

First, based on Green Building design examples in Taiwan and expert interviews, the possible natural ventilation design techniques were determined. Then, with the aim of optimizing natural ventilation ducts and the interconnected space, the investigated model space was obtained via reasonable physical modeling, as shown in Fig.1. The red-dotted area shown in Fig.1 is the key observation of our study. The installation requirements and the design details of the natural ventilation shaft in the investigated model space come from Clause 43 (Ventilation) and Clause 44 (Construction of natural ventilation equipment) in the Taiwanese Building Code.

3. Experimental Equipment

To mimic the investigated model space, a full-scale smoke-flow room was designed and established at the outdoor experimental site of ABRI (Architecture & Building Research Institute), Ministry of the Interior, Taiwan, as shown in Fig.2., with its direction facing south and a glass window in the east side for observing the conditions of the smoke layer or flow. Type K thermocouples were equipped internally, as shown in Fig.3., to measure air temperature.
3.1 Calculation of the smoke layer descent
The smoke descent curve was traced by the temperatures as measured by thermocouples according to the N-percentage as proposed by (Copper, 1981).

3.2 Experimental process
Six experimental scenarios were tested in this study by using a 50 kW oil pan to generate thick smoke with Door 1 and Door 3 in a natural ventilation status. An electric fan was placed at the natural ventilation shaft opening and blew the air with a constant velocity horizontally through the vertical opening to mimic an outdoor wind. A video recorder was utilized to record the smoke flow. Table 1. presents the deployment of the various fire scenarios.

4. Results and Discussion
A breathing zone at a height of 1.5 m was set up in the experiments to indicate that when smoke falls to this height, it will choke a human and result in evacuation difficulties. Therefore, the following discussion is based on the reference of smoke falling to 1.5 m, where $T_{150}$ is the time required from the beginning of the experiment to the smoke layer falling to 1.5 m, which is shown in Table 2.

**4.1 Temperature changes of No. EXP 0-0a.**
Shown in Fig.6. are the experimental temperature changes of EXP 0-0a. As the oil pan was ignited 120 seconds after the start of the experiment, we can see that the two thermocouples (TC2 and TC3) that

### Table 1. Fire Scenario of Full-Scale Smoke Flow Experiment

| Experiment no. | Setting                    | Location of fire source |
|----------------|---------------------------|-------------------------|
| EXP 0-0a       | Closed natural ventilation shaft | Room 1                  |
| EXP 0-0b       | Closed natural ventilation shaft | Room 2                  |
| EXP 0-1        | Open natural ventilation shaft | Room 1                  |
| EXP 0-2        | Open natural ventilation shaft | Room 2                  |
| EXP 0-3        | Outdoor wind speed 5m/s      | Room 1                  |
| EXP 0-4        | Outdoor wind speed 5m/s      | Room 2                  |

### Table 2. Time Lapse for the Smoke Layer to Fall to 1.5 m in Various Scenarios

| Room     | Location of the fire source | Natural ventilation shaft | Outdoor wind speed | $T_{150}$ (after ignition) | Experiment no. |
|----------|-----------------------------|---------------------------|--------------------|----------------------------|----------------|
| Room 1   | without                      | No                        | 97 s               | 181 s                      | EXP 0-0a       |
| Room 1   | with                        | Gentle breeze (<1 m/s)  | 86 s               | 206 s                      | EXP 0-1        |
| Room 1   | with                        | 5 m/s                     | 80 s               | 195 s                      | EXP 0-3        |
| Room 1   | without                      | No                        | 160 s              | 59 s                       | EXP 0-0b       |
| Room 2   | with                        | Gentle breeze (<1 m/s)  | 182 s              | 66 s                       | EXP 0-2        |
| Room 2   | with                        | 5 m/s                     | 187 s              | 50 s                       | EXP 0-4        |

Fig.6. The Temperature Changes of EXP 0-0a
were nearest to the fire source began to rise after 120 seconds. TC1 also rose at approximately 140 seconds, indicating that the smoke approached Door 1 after 20 seconds and then started to descend from the ceiling. At approximately 190 seconds, the temperature of TC4-5 started to rise. The rise in speed occurred faster than it did with TC4-1 because TC4-5 was the temperature detector of the door, and the smoke flowing from Room 1 first passed through TC4-5 and then TC4-6 before flowing upward to reach the ceiling of Room 2. TC5 and TC6, however, only started to rise at approximately 200 seconds. This result shows that when a fire occurs, the smoke will flow into the non-fire room at approximately 80 seconds and start to accumulate there.

4.2 Temperature changes of No. EXP 0-0b

Fig.7. shows the temperature changes of EXP 0-0b. It is revealed that at the initial fire stage, the temperatures of TC5 and TC6 started to rise, and the smoke started to descend from the ceiling; when the smoke dropped to the door height, it began to flow into Room 1. Thus, the temperatures of TC1, TC2 and TC3 only increased at approximately 200 seconds. We can therefore assume that 80 seconds after the fire started, the smoke had flowed to the adjoining room and started to descend.

As the smoke flow trend of the three groups of experiments EXP 0-1 and EXP 0-3 was similar to EXP 0-0a and the smoke flow trend of the three groups of experiments EXP 0-2 and EXP 0-4 was similar to EXP 0-0b, with a difference of only a few seconds, they will not be described again here.

4.3 The influence of the natural ventilation shaft on the smoke layer descent when the fire source is located in Room 1

Fig.4. shows the influence of the natural ventilation shaft on the smoke layer descent when the fire source is located in Room 1. The smoke layer descent in the on-fire room (Room 1) has almost nothing to do with the natural ventilation shaft, with three curves overlapped together, as shown in Fig.4.(a). The smoke layer fell to the 1.5 m height after the oil pan had been ignited for approximately 80 s, and it reached a stable status after another 100 s; the smoke layer height was at approximately 1.2 m.

Meanwhile, the smoke layer descent curve (Fig.4.(b)) of Room 2 indicates that the scenario EXP 0-0a (without the natural ventilation shaft) is the fastest to fall to 1.5 m because there is nowhere for the smoke to be expelled to. The smoke cooled when it flowed from Room 1 into Room 2, and the upper layer of smoke in these three scenarios in Fig.4.(b) only reached approximately 50°C. Due to the lower temperature, the smoke could not be expelled effectively via the thermal buoyancy effect. Indoor smoke cannot be
exhausted significantly with the partial negative pressure created when outdoor wind passes through the shaft outlet; thus, installing a natural ventilation shaft can effectively extend the time for the smoke layer to descend, but induced smoke flow through the shaft by the outdoor wind is not so obvious.

4.4 The influence of the natural ventilation shaft on the smoke layer descent when the fire source is located in Room 2

Fig. 5. shows the influence of the natural ventilation shaft on the smoke layer descent when the fire source is located in Room 2. When it is on fire for approximately 60 s, the smoke in the fire room (Room 2) falls to a height of 1.5 m. The descent is faster than the above case when the fire source is located in Room 1, which has a larger air volume. This result indicates that the smoke layer in both rooms sinks in the order of EXP 0-0b>EXP 0-2>EXP 0-4.

The smoke temperature in the fire room reaches as high as 90°C. Thus, the buoyancy effect and induced flow in the natural ventilation shaft should be more significant, as the effect effectively expels the smoke and delays the smoke descent speed. Meanwhile, the partial negative pressure created when the outdoor wind passes through the shaft opening causes a slight increase in the smoke layer height of Room 2, showing that the expelled smoke has a greater expelled volume than that of the natural ventilation with a slight outdoor breeze. From the non-fired Room 1, it is also found that the operation of the natural ventilation shaft in the adjacent room (Room 2) extends the smoke sinking speed, which effectively lifts the smoke layer height as well.

5. Conclusion

In view of the space type, as studied in this research, when a natural ventilation shaft is not installed in the fire room, the sinking of the smoke layer has less to do with whether the natural ventilation shaft is set up in the adjacent room. The temperature of the upper layer of smoke in the adjacent non-fired room equipped with a natural ventilation shaft is not high because the thermal buoyancy is not significant; thus, the smoke will accumulate in the shaft and will only be expelled by an outdoor wind-induced force. Setting up a natural ventilation shaft can effectively extend the smoke sinking time in the adjacent non-fired room, but the outdoor wind-induced force did not seem to have much effect.

When a fire occurs in a room with a natural ventilation shaft, because the smoke temperature in the fire room is higher, the thermal buoyancy effect in the shaft will be more significant. Hence, the smoke exhaust effect in the natural ventilation shaft is better, and such effective smoke exhaustion is able to delay the smoke layer descent and increase the smoke layer height. Meanwhile, with the help of outdoor wind, the traction force at the natural ventilation shaft would play its part, causing the average smoke layer position to be higher than if it were not subjected to outdoor wind traction force, thus extending the time available for the safe evacuation of people in a fire scenario.

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