SCALE MODELING OF NATURAL VENT DESIGN AND THE EFFECT OF VENT OPERATION TIME

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ABSTRACT

Experimental studies on natural smoke filling process and performance of natural vents in an atrium fire will be carried out in a 1/20 scaled model of the full-scale burning facility: PolyU/USTC Atrium in Hefei, Anhui, China. Different scaling parameters between the full-scale facility and the scaled model are derived from scaling laws. Thermocouples were calibrated with the errors in temperature measurement identified. Vertical temperature distribution and descending time of the smoke layer were recorded during the preliminary test. In addition, future planning of the research project will be stated.

1. INTRODUCTION

In Hong Kong, atrium buildings are very common especially for shopping malls and commercial areas since it can provide an indoor environment with greater space visually. However, the huge volume of atrium will provide sufficient air for the entrainment of fire plume in case of a fire. A large amount of smoke will then be generated and spread rapidly to the adjacent areas and other floors. Since smoke is recognized as the major killer in fire situations [1], it is realized that the safety of occupants can be improved significantly by providing a more efficient smoke control system.

Experimental studies on natural smoke filling during an atrium fire in a full-scale burning facility were performed [2,3] to study the smoke interface height, vertical temperature profile, thickness and descending time of the smoke layer. The results are consistent with those in the literatures [e.g. 1,4]. Furthermore, the locations of vents, areas of vent openings and the volume of atrium would affect the smoke extraction mechanism [5].

Different techniques [6] can be designed to control smoke spreading. But the fire scenario and the associated problems on fire safety design are special for atrium buildings. Natural ventilation may be the cheapest way to achieve smoke control as the system needs only the installation of natural ventilators, provided that the outdoor temperature is lower than that of indoor in case of fire. In Hong Kong, natural vent design has been adopted in some atrium buildings such as the Olympic City. Natural ventilators available in the market have a great variety of dimensions to meet what the market needs [7]. All products should comply with BS7346: Part 1 [8] to pass certain tests on rain and wind resistance; fire and heat; temperature rise and expansion; and coefficient of performance test for smoke exhaust.

Since most of the experiments were carried out in enclosed atria and the existing smoke control systems focus mainly on mechanical exhaust systems, only a few studies were related to natural ventilation. The purpose of this paper is to study the smoke behaviours on natural vent design and to investigate the differences of smoke extraction mechanisms at different operation times of vents with different number of ceiling vents in order to serve as a guideline for future smoke control design.

2. SCALING LAW

Dimensionless parameters (π groups) were introduced by Quintiere [9] to establish the 'laws of scaling'. The concept was based on the conservation equation for air flow:

Mass:

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u)}{\partial x} = 0 \qquad (1)$$

Momentum:

$$\rho \frac{\partial u}{\partial t} + u \frac{\partial (\rho u)}{\partial x} = -\frac{\partial p}{\partial x} + g(\rho_a - \rho) + \frac{4}{3} \mu \frac{\partial^2 u}{\partial x^2} \qquad (2)$$

where

$$\frac{dp_a}{dx} = -\rho_a g$$

and

$$p' = p - p_a$$

Energy:

$$\rho c_p\left(\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}\right)=k\frac{\partial^2 T}{\partial x^2}-4\kappa\sigma T^4+\int_0^{4\pi}\kappa I d\omega+\dot{Q}^m+\frac{\partial p}{\partial t} \quad (3)$$

The above equations are transformed into dimensionless form with appropriate normalizing parameters defined. Independent dimensionless groups (π-groups) are derived:

$$\pi_1=\frac{L}{Vt_0}, \quad \pi_2=\frac{p_*}{\rho_0 V^2},$$

$$\pi_3=\frac{\mu}{\rho_0 VL}=\frac{1}{Re}, \quad \pi_4=\frac{gL}{V^2} \quad (4)$$

Equating one of the π parameters to 1 would give a characteristic normalizing parameter in terms of other variables. This procedure can eliminate that π effectively and some π groups are related to more common dimensionless groups.

$$\pi_1=\frac{L}{Vt_0}=1, \quad \pi_2=\frac{p_*}{\rho_0 V^2}=1,$$

$$\pi_3=\frac{\mu}{\rho_0 VL}=\frac{1}{Re}, \quad \pi_4=\frac{gL}{V^2}=\frac{1}{Fr^2} \quad (5)$$

where Re is the Reynolds Number and Fr is the Froude Number.

Consequently, the scaling law is as follows:

$$\frac{\dot{Q}_m}{\dot{Q}_r}=\left(\frac{L_m}{L_r}\right)^{5/2}, \quad \frac{t_m}{t_r}=\left(\frac{L_m}{L_r}\right)^{1/2},$$

$$\frac{V_m}{V_r}=\left(\frac{L_m}{L_r}\right)^{1/2} \quad (6)$$

where Q is the heat release rate (kW); L is the characteristic length (m); t is the characteristic time (s) and V is the characteristic velocity (ms^{-1}). The suffix m refers to the model and r refers to the real scale.

3. SCALED MODEL

A 1/20 scaled model based on the PolyU/USTC Atrium was made. This atrium is chosen as a reference because full-scale experimental studies on natural smoke filling had been carried out [2,3]. The results obtained by using that full-scale burning facility and using the scaled model can be compared if there is any discrepancy. Ideally, experiments conducted in full-scale would be more accurate and convincing. However, due to its expensive cost and safety reasons for conducting the experiments with real fire, the number of tests would be limited. Performing experiments with scaled model would be appropriate because of its effective cost and repeatability.

The scaled model is made of acrylic plates with internal dimensions of 1.12 m (length) × 0.595 m (width) × 1.35 m (height), with a 0.01 m vertical gap on one side for supplying air. Two other ceiling plates with two vents and eight vents, which are evenly and centrally located, were made to study the effects on different ceiling design. The details of the model and the experimental setup are shown in Fig. 1 and Fig. 2.

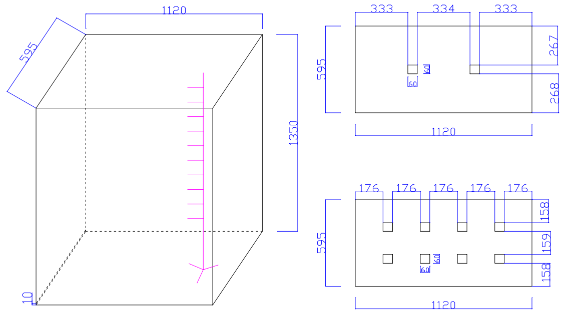

Fig. 1: Dimensions of scaled model and ceiling plates

Fig. 2: Scaled model and experimental setup

4. PRELIMINARY TEST

4.1 Fire Size

In the experiment, liquid fuel (propanol) was used and ignited as a fire source with 1.45 kW heat release rate [10] with a pool diameter 0.05 m (this corresponds to 2.6 MW and 723.3 kW fire sizes with pool diameters of 1 m and 0.6 m respectively according to the scaling law [9]). Actually, the main function of the fire source is to ignite the smoke cartridge to generate smoke for visualization, so the fire size should not be too large.

4.2 Smoke Generation

Since the combustion of propanol was not clear, it was difficult to visualize the smoke movement pattern. Therefore, smoke cartridge with burning time about 65 s was used to generate grey smoke for visualization. Since the smoke cartridge generates smoke after ignition until it is used up, it is suitable to use the smoke cartridge with short burning time about 60 s in order to control the amount of smoke generated.

4.3 Temperature Measurement

To measure the vertical temperature distribution of the fire plume with high frequency response, type K thermocouples with a pair of dissimilar wires were used. The signals from the thermocouples were sent to the computer by connecting the thermocouple with the data logger (DaqView 7.12.8).

A thermocouple rack should be set up in order to measure the vertical temperature distribution of smoke layer inside the model. Ten thermocouples were installed along the thermocouple rack with 0.1 m spacing starting from 0.35 m to 1.25 m above the ground level as shown in Fig. 2. T1 is at the top while T10 is at the bottom of the thermocouple rack.

Before using the thermocouple rack in the research experiment, it should be calibrated to identify the errors in temperature measurement. Two calibration tests were carried out, one by melting ice and the other one by boiling water. The calibration test setup is shown in Fig. 3. The results are shown in Fig. 4.

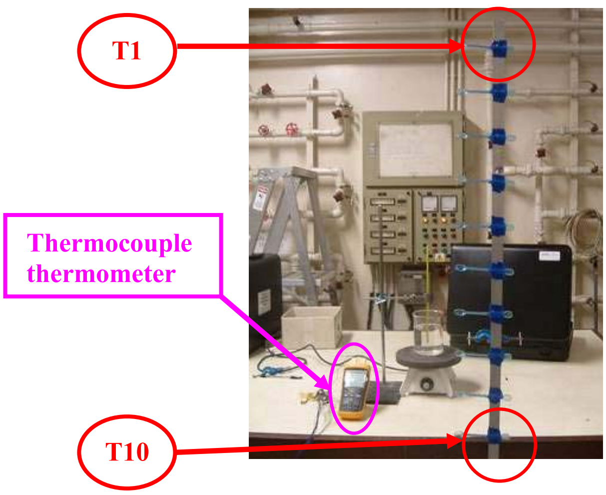

Fig. 3: Calibration test of thermocouple

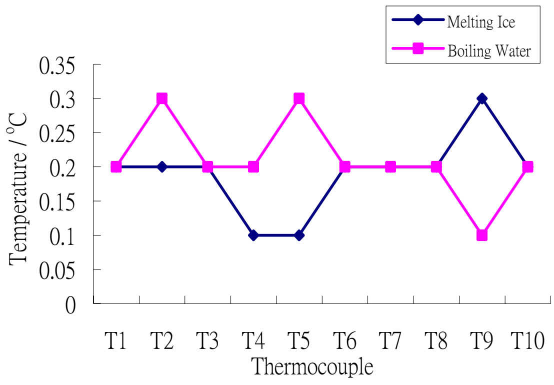

Fig. 4: Errors of thermocouples

From the results, it was found that all the thermocouples had little errors ranging from 0.1 °C to 0.3 °C in measuring temperatures. By comparing the errors of a particular thermocouple in two tests, it can be found that the errors may not be the same even for the same thermocouple (see Fig. 4). It might be due to the fact that the sizes of the welded joint of the two dissimilar wires were different. In addition, the ice water or boiling water might not at a uniform temperature in the beaker.

4.4 Smoke Layer Interface Height

The positions of smoke layer interface were inspected visually according to NFPA 92B [11] on vertical smoke density distribution. In the model, three positions, 30 cm (t_{30}), 60 cm (t_{60}) and 90 cm (t_{90}) down the ceiling, were marked. The time at which the smoke layer descended to those positions, as well as reaching the floor (t_{fl}), were recorded. The experimental setup is shown in Fig. 5.

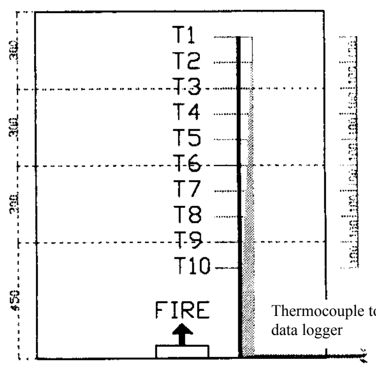

Fig. 5: Measurement of vertical temperature profile and position of taking descending time

5. RESULT OF PRELIMINARY TEST

5.1 Vertical Temperature Profile

In order to have significant comparison, two sets of preliminary tests were carried out. One was on smoke filling process with all the vents closed while the other one was with all ceiling vents (8 vents) opened. After getting the results of the smoke layer temperature from the data logger, the vertical temperature profiles against time of the two cases can be determined. The results are plotted in Fig. 6 and Fig. 7. To have clearer interpretation of the results, only five curves are shown in each case.

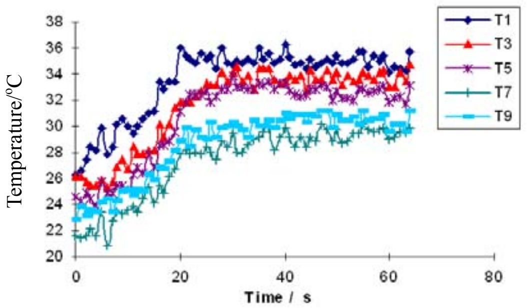

Fig. 6: Vertical temperature profile with no vent

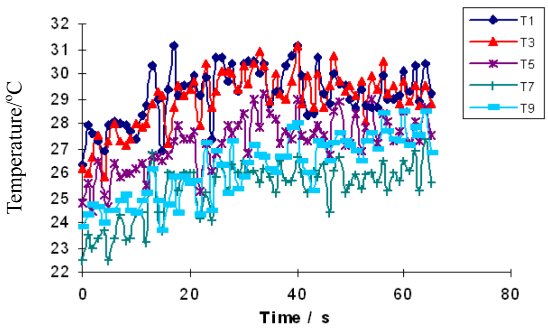

Fig. 7: Vertical temperature profile with 8 vents

From the results, it was found that the air temperature increased gradually after the fire had started and the temperatures recorded at higher level were higher than those at lower level in both cases. This may due to the fact that the air at lower level was heated by the fire source and rose by buoyancy effect, causing the hot air to rise. The cool air in the surrounding inside the model might be entrained into the fire plume at lower level, making the temperature at lower level a little bit lower.

It was also found that the temperature rise in the case with all vents closed was greater than that with all vents opened. This was because if the vents were opened, the hot air and the smoke could escape or extract out of the model as soon as they reached the ceiling. Less smoke and hot air would be accumulated inside the model, so the air temperature would be lower as heat loss by convection occurred. On the other hand, if the vents were all closed, hot air and smoke would be accumulated inside the model, making the air temperature at higher level to be higher. This could explain why the temperature at the higher level of the model rose faster and obtained the highest temperature as shown in Fig. 6.

5.2 Descending Time

As shown in Table 1, it can be seen that the descending time for the case with 8 vents opened was longer than that with all vents closed. This was because the smoke could escape out of the model through the vents, allowing the rate of smoke filling to be slower. For the other case, as there was no vent for the smoke to extract, the smoke reaching the ceiling would be trapped and circulate inside the model by convection, making the smoke filling rate to be faster.

Table 1: Descending time of smoke layer

Thickness of smoke layer / cm	All vents closed	All vents opened
30	15.22 s	22.53 s
60	18.35 s	27.20 s
90	20.10 s	35.24 s
135 (ground level)	30.38 s	42.83 s

6. FUTURE PLANNING

Since there was significant difference in smoke filling between an enclosed atrium and an atrium with vents opened, more experiments would be carried out to find out the differences between the smoke extraction mechanism of different ceiling design and the effect of vent operation time. After carrying out the preliminary tests, some precautions, such as attaching a time counter along the video clip to show the time during the smoke filling process, were learnt which would be useful for conducting the research experiment in the next semester.

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Q & A

Q1: How can you judge or determine the smoke layer interface?

Chan: According to NFPA 92B, I just determine the smoke layer interface by visual observation.

Q2: You have considered the horizontal vent. Have you considered the vertical vent?

Chan: Not yet, but it will be included in future study.

Q3: Have you considered any environmental impact?

Chan: Not yet, but it will be included in future study.