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EXPERIMENTAL STUDIES ON SMOKE FILLING IN ATRIUM FIRES

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ABSTRACT

Experiments on smoke filling during an atrium fire were conducted in a reduced-scale compartment which was constructed to be a 1/8 scale modeling of the PolyU/USTC Atrium. The steady-state fire experiments were conducted and the distributions of temperature and smoke visibility were measured. The result indicates that the stratification effect between the upper layer and lower layer can be discerned in the smoke natural filling process, but its interface is obscure being thick transition zone. It also can be found that the time required to fill an atrium with smoke is much shorter than expected and installing a smoke extraction should be recommended. The data obtained in this experiment were compared with those obtained in the full-scale prototype experiments through the preservation of the Froude number. Good results were achieved between the model and prototype for natural smoke filling. It showed that the Froude number was reasonable, and the approach to use reduced-scale model technique for studying the natural smoke filling with pre-flash fire was practicable.

1. INTRODUCTION

In recent years, the atrium building has become commonplace in China. This concept is widely adopted by architects in designing modern buildings, such as luxurious hotels, multi-level shopping centers and prestigious office buildings. The design is so popular because a comfortable environment can be provided. Most of the atrium floors are well decorated with plants or even musical ponds and can be used for exhibition, entertainment, performance and catering. They are often crowed with people, which is highly desirable for the developers in using the building as a shopping mall even though its construction costs are very expensive.

An atrium within a building is a large open space created by an opening or series of openings in floor assemblies, thus connecting two or more stories of a building, which is closed at the top. The sides of an atrium may be open to all floors, to some of the floors or closed to all or some of the floors by fire-resistant construction. As well, there may be two or more atria within a single building, all interconnected at the ground floor or on a number of floors.

By interconnecting floor spaces, an atrium violates the concept of floor-to-floor compartment, which is intended to limit the spread of fire and smoke from the floor of fire origin to other stories inside a building. With a fire on the floor of an atrium or in any space open to it, smoke can fill the atrium and connected floor spaces. The fire risks of atrium buildings are different from those of traditional buildings, and the associated problems related to smoke should be dealt with carefully. Therefore smoke movement and smoke management in an atrium is one of the most important life safety considerations in atrium development and studying this becomes a research focus in the fire engineering fields.

There is no full set of codes and regulations in Mainland China to govern the atrium design. Code for Fire Protection Design of Tall Buildings (GB50045-95) provides some regulations of fire safety in atrium building [1]. The air change rate method is taken for designing a smoke extraction system. Obviously these regulations are not good enough for designing a workable extraction system. It is not reasonable to use the volume of atrium space as a design criterion for designing smoke extraction system. The geometrical configuration should be included. Fire size and the risks posed by the position of a smoke layer interface may also be considered in the requirements [2]. Furthermore, the performance-based building code was introduced in many countries, such as Japan, New Zealand and Australia [3]. Therefore, further research on atrium fire is urgently required in order to support the development of performance-based codes in China.

Apart from the numerical simulations of fire environment using computer models, experimental studies are also good ways to study the smoke movement and smoke filling process in atrium fires. Experimental studies with full-scale models are good but too expensive and time consuming. On-site measurement in an actual atrium would be constrained if using 'cold smoke'. Experimental studies with reduced-scale models are alternative to the full-scale tests. The obvious advantages of studying fire problems at a reduced size are less costly and easy operation.

In this study, an experiment studying the smoke-filling behaviors in atrium fire was conducted in a reduced-scale compartment, which was constructed to be a 1/8-scale modeling of the PolyU/USTC Atrium. The steady-state diesel fire with pan diameter 125 mm was located at the center floor with all the windows and vents of the atrium closed, leaving just a vertical gap on the bottom of east wall for supply fresh air. The distributions of temperature and smoke visibility were measured.

2. DESCRIPTION OF THE EXPERIMENT

2.1 Reduced-Scale Atrium Model

The reduced-scale atrium was designed to be a 1/8 scale model of the Large Space Fire Experimental Hall co-constructed between Hong Kong Polytechnic University and University of Science and Technology of China [4] (PolyU/USTC atrium).

Froude modeling was used as the scaling law of smoke movement in atrium in this study. Scaling relationships are provided in NFPA 92B for the physical modeling of Atrium space. The scaling expressions are as follows [5]:

$$x_m = x_F\,(L_m/L_F) \qquad (1)$$

$$\tau_m = \tau_F\,(L_m/L_F)^{1/2} \qquad (2)$$

$$T_m = T_F \qquad (3)$$

$$Q_{c,m} = Q_{c,F}\,(L_m/L_F)^{5/2} \qquad (4)$$

where x is the position, L is the length, τ is the time, T is the temperature, and Q_c is the convective heat release rate; the subscripts F refers to full-scale, and m refers to reduced-scale model.

Fig. 1 schematically depicts the experimental facility used for this study. The facility is a compartment with interior dimensions of 2.8 m length by 1.49 m width by 3.38 m height with a door on the center of the south wall. The door has a width of 0.8 m and a height of 1.5 m. The door and the ceiling were made from fire-protected materials. The concrete bricks were used for the walls. A fan was used to exhaust smoke from the compartment through the opening in the West wall as shown in Fig. 1. The two inlets were designed on the bottom of both East and West wall. The three inlets were designed on the bottom of the North wall. The two inlets on both sides of door were designed on the bottom of the South wall. These inlets had a width of 30 mm and height of 20 mm. To allow for visual observation within the compartment, a glass strip observation window in the center of the East wall was outfitted. And four electric lamps were installed on the interior West wall. The different size diameter fuel pans were located at the center of the compartment respectively [6].

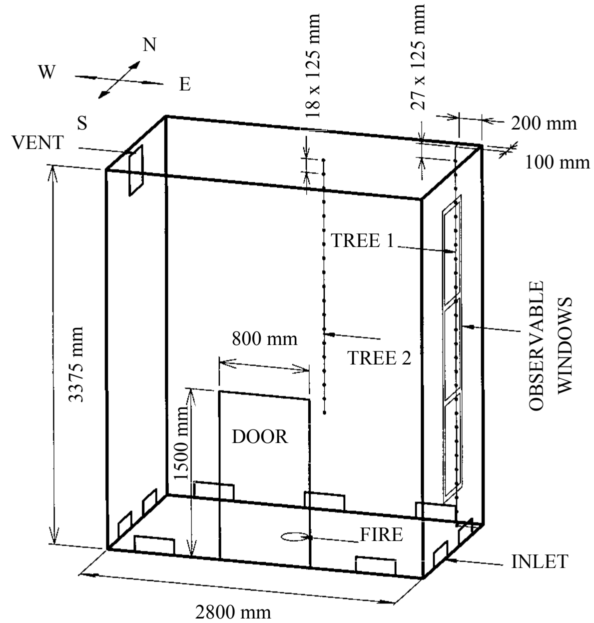

Fig. 1: Sketch of an atrium model

2.2 Instrumentation

Inside the test compartment there were two vertical thermocouple trees. A set of 26 thermocouples with 125 mm intervals was vertically placed at the northeast corner of the compartment. A second set of 18 thermocouples with 125 mm intervals was also vertically placed at the center of the compartment over the fuel fire source, as shown in Fig. 1.

The diesel was burned as the fire source in the fuel pan. A weighing system was established to record the mass of fuel during the experiments. The mass release rate was deduced from derivative of record against time during burning.

During the test, the door, vent and inlets were closed, except one inlet on the east wall was opened. One computer was used to monitor and record data collected by thermocouples and weighting sensor. Data were recorded every 12 seconds during the test times on a high-speed multi-channel data acquisition system. And the smoke-filling behavior was captured on a digital camera.

3. EXPERIMENTAL RESULTS AND DISCUSSION

A series of fire experiments with different heat release rate has been conducted. Experiment for each heat release rate was repeated 3 times. The average measured values of temperature data were used for analysis. The results presented in this paper are the case where the arrangement was for the steady-state fire associated with a 125 mm diameter fuel pan located in the center of the compartment. The fuel weight losses measured in the test are given in Fig. 2. The heat release rate obtained by converting the average mass-burning rate in Fig. 2 is a constant 3.59 kW, with the effective heat of combustion of the diesel taken as the value of 42000 $kJkg^{-1}$. This value corresponds to a constant heat release rate 650 kW in prototype.

Fig. 3 shows the measured results of temperature profile of the thermocouple tree 1 located in the northeast corner as a function of time. The following conclusions can be made from Fig. 3: At the beginning of the ignition, the temperatures are almost constant from the bottom to the top of the thermocouple tree. It should be noted that the experimental data taken from the measurements during 1-2 minutes after the ignition show that the temperatures close to the ceiling increase markedly and then all the temperatures increase uniformly. The descent of the smoke layer is very quick at the first burning period but slows down later. This is attributed to the fact that the rate of air entrainment from the lower layer decreases as the smoke layer descends further. The vertical temperature distribution with smoke tends to be non-uniform with a temperature gradient from the floor to the ceiling. Temperature continuously increased with height up to the region near the ceiling. Stratification effect can be discerned from the temperature changes along the vertical direction at given times. However, the temperature distribution does not indicate a distinct interface between the hot upper layer and the relatively cool lower layer. The temperature continuously increased with height from floor up to the region near the ceiling of the model. The hot gas temperature is not too high. It also indicates that it takes about a litter less than 3 minutes for smoke to descend the floor in the atrium model. This means that the smoke will fill of the whole full-scale prototype atrium space with the height 27 m in about 8 minutes. It is illustrated that smoke would be the major cause of hazard during an atrium fire, and installing a smoke control system is recommended.

The photographs of smoke layer height prediction captured by a digital camera are shown in Fig. 4. At the beginning of starting burning, the luminous intensity of three lamps is the same. The luminous intensity of the bottom lamp is less bright than that is in about 1 minute after ignition. It is because the hot product gas, soot and air mixture driven by buoyancy forces trends to move upwards, accumulating under the ceiling after starting burning. The density of smoke in the hot upper layer is higher than that in the lower layer. After 3 minutes, as can be seen, the visibility through fire smoke is obscure. Needless to say, the compartment is full of smoke. In addition, a thick transition zone was observed by eye.

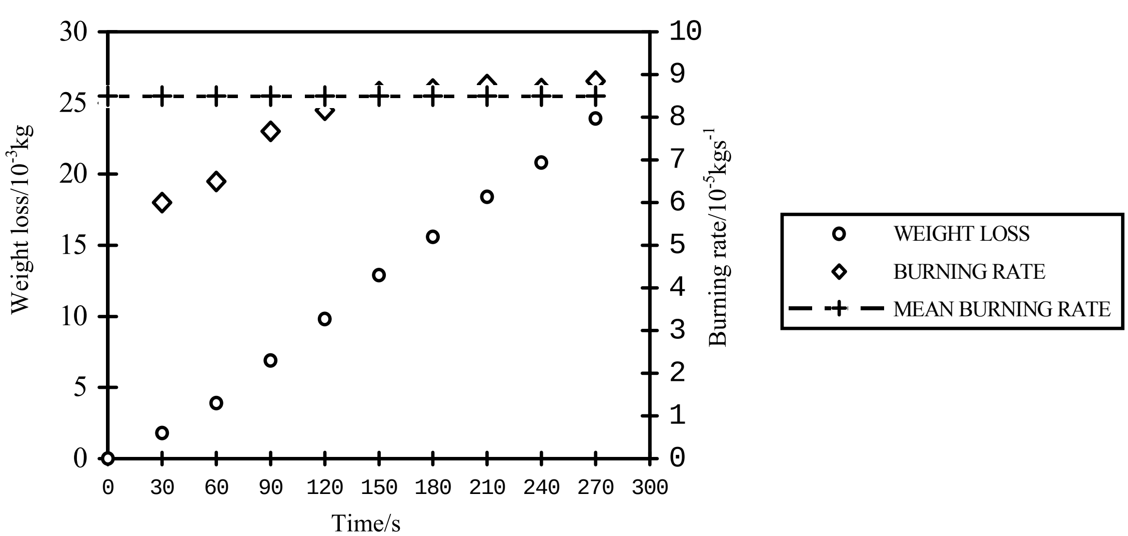

Fig. 2: Heat-release rate in diesel oil fire

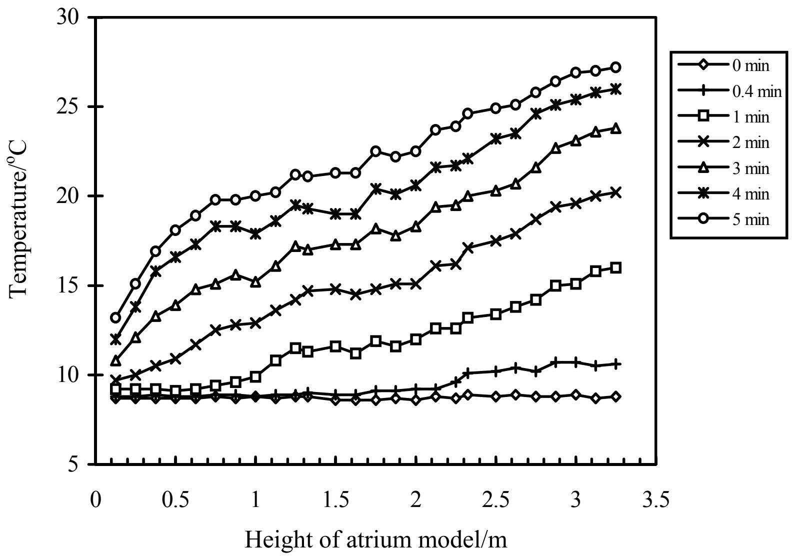

Fig. 3: Vertical temperature distribution versus time

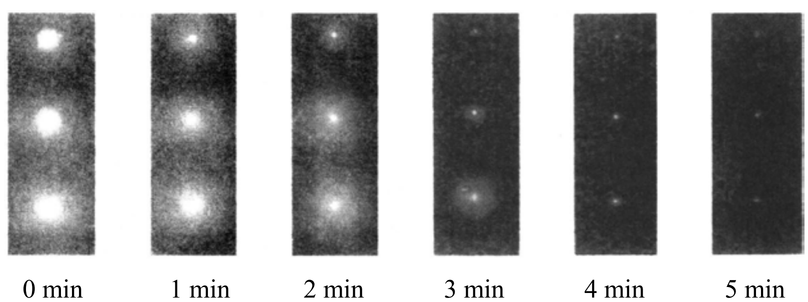

Fig. 4: Distribution of smoke density and visibility versus time

It is remarkable that the same general trends predicted by the distribution of smoke density show as those noted in the distribution of the temperature profile in Fig. 3. But there is a fine discrepancy between two distributions. A time delay was observed for the descent of the smoke layer from temperature distribution. In other words, the development of smoke determined from smoke visibility distribution in photograph is quicker than that determined from temperature distribution. It is probably due to the reason that the thermocouple has a time lag. Mass transfer via convection and diffusion are the two mechanisms that govern the distribution of smoke density. Heat transfer via convection, conduction and diffusion are the three mechanisms, on the other hand, that govern temperature distribution. Therefore, the two distributions are not similar to each other. The correlation between the smoke decent as determined from temperature distribution and that as determined from smoke density or visibility distribution need further study.

The data obtained in this experiment by converting with Froude number Law were compared with those obtained in the full-scale prototype experiments [7]. Obviously, the temperature distribution does not indicate a distinct interface between the hot upper layer and the relatively cool lower layer. Temperature continuously increased with height up to the region near the ceiling of the model. In this study, the interface height was determined by using the N-percentage rule to process experimentally measured temperature data [8]. Fig. 5 shows a comparison of the development of smoke layer height between the model and the full-scale atrium. It is obvious that the small-scale data do correlate well with the prototype atrium data. This illustrates that the Froude modeling is reasonable for predicting smoke temperature, and the approach to study the smoke natural filling process of atrium pre-flashover fire using reduced-scale model technique was practicable.

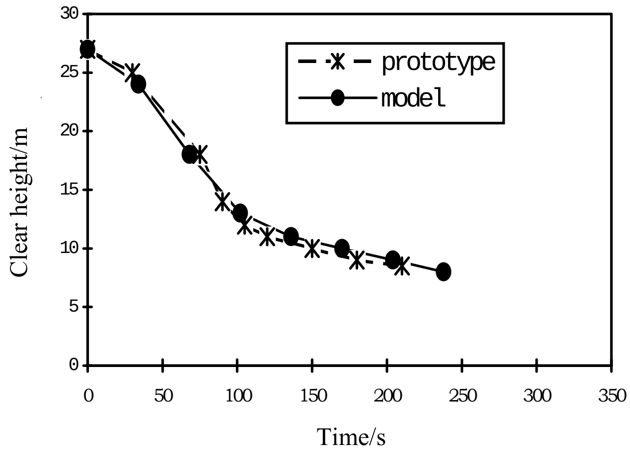

Fig. 5: Comparison between measured smoke layer height for reduced-scale model and full-scale model prototype

4. CONCLUSION

From the result of this study, it may be concluded that:

In the smoke nature filling process, the stratification effect between upper layer and relatively cool lower layer can be discerned, but its interface is not distinct. There is a thick transition zone.

It is illustrated that smoke would be the predominant cause of hazard and installing a smoke management system is recommended.

The Froude modeling is reasonable for predicting smoke temperature and the development of smoke layer, and the approach to use reduced-scale model technique for studying the natural smoke filling with pre-flashover fire was practicable.

Further studies on the development of smoke layer in the modeling atrium under ventilation are needed.

ACKNOWLEGEMENT

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