Fire Safety Journal 100 (2018) 20–31

Contents lists available at ScienceDirect

Fire Safety Journal

journal homepage: www.elsevier.com/locate/firesaf

Prediction of natural and hybrid ventilation performance used for fire-induced smoke control in a large single space

Yan Tong [a], Dekai Huo [a], Peigen Zhu [b,*], Xiaofeng Niu [a]

[a] College of Urban Construction, Nanjing Tech University, Nanjing, Jiangsu, 210009, PR China
[b] National Defense Engineering Institute, PLA University of Science and Technology, Nanjing, Jiangsu, 210007, PR China

ARTICLE INFO

Keywords:
Large space
Fire smoke
Roof opening
Hybrid ventilation
Natural ventilation

ABSTRACT

This paper deals with a large single space building for smoke control when a fire happens. Two hybrid ventilations are investigated, i.e. natural ventilation through a roof opening combined with mechanical suction flow, and with mechanical jet flow. Pure natural ventilation is used as a benchmark. An experimental model was reproduced as 1/10 of the prototype. Under pure natural ventilation, the roof opening played an important role in exhausting but the smoke layer height descended rapidly. Influences of mechanical flows from sidewalls on the smoke distributions were found to be evident. Large eddy full-scale simulations were performed in which grid size of the fire-domain was determined to be 0.125 m being one half of the non-fire domain. The simulation results agreed well with the experimental ones. A total of 63 ventilation cases are further simulated, and it reveals that mass flow rates of the roof opening increase with the increase of opening area ratio or discharge velocity of inlets or heat release rate but with the decrease of exhaust velocity of outlets; under hybrid ventilation of mode 4, back-flow occurs under the roof opening when the exhaust velocity reaches up to 6 m/s, and the maximum smoke temperature and the CO concentration near the door is of the lowest indicating its best advantage in controlling the fire smoke; the smoke plume is more easily disrupted by jet flow than by suction flow. This study helps to promote the design and operation of ventilation system for large and high spaces when firing.

1. Introduction

With the rapid development of urbanization in China, the number of public buildings is increasing, such as atrium, mall, stadium, railway station and terminal. Such buildings are often large and high, and occupied with a lot of people. In case of firing, smoke and toxic gases are the most fatal factor, and it would spread quickly and far because the smoke compartmentations are often difficult to be installed, so an effective smoke control ventilation system will play an important role.

In large and high spaces, roof openings are often set to achieve natural ventilation and daylighting. Chow [1,2] proposed that as long as a roof opening was designed properly, only natural ventilation may be effective in smoke control even in a large-scale fire. Qin [3,4] investigated smoke filling processes under different natural and enhanced smoke exhaust methods, and found out that natural smoke exhaust method was preferred when the smoke exhaust vents were located at the ceiling of the gymnasium/atrium. In some performance-based fire designs [5–7], pure natural ventilation have also been adopted. But natural ventilation has an intrinsic defect of instability, and its application has been restricted severely in most fire codes.

Some studies have been done on mechanical smoke exhaust in firing. Ji [8] conducted a set of burning experiments to investigate the influence of exhausting velocity on mechanical smoke exhausting efficiency, and found out that the plug-holing would happen with the increased exhausting velocity, and in the tests without the plug-holing, the fresh air entrained due to smoke exhausting is up to 48% of the mechanical exhausting rate. Qin [3,4] used the Fire Dynamics Simulator (FDS) code to investigate the smoke movement, and revealed that when the smoke exhaust vents are located on the walls of the atrium/gymnasium, the higher positions of the smoke exhaust vents are preferred. Li [9] conducted small-scale modeling experiments for a hydropower station, and revealed that the smoke exhaust process was less efficient when the heat release rate was larger, and better smoke control may be obtained with larger smoke exhaust rates.

Air supply has advantage of not hindering the escape route and sometimes can be used as smoke compartmentation. Hu [10] studied the possibility of utilizing air curtain for confinement of fire-induced smoke and carbon monoxide transportation along channels and found out that

* Corresponding author.
E-mail address: 412020242@qq.com (P. Zhu).

https://doi.org/10.1016/j.firesaf.2018.03.005
Received 15 December 2016; Received in revised form 14 January 2018; Accepted 23 March 2018

the gas temperature and CO concentration in the protection zone reduced significantly by an exponential trend with the increase of discharge velocity of the air curtain. Gao [11] studied a breathing air supply zone combined with an upward ventilation assisted tunnel evacuation system (BTES), and revealed that the carbon monoxide (CO) concentrations with the BTES were significantly lower than that with the traditional ventilation system. Nuo [12,13] confirmed that for a high-rise building fire, air curtain could play a good role on controlling smoke diffusion and the discharge velocity could influence the efficiency of air curtain, and further proposed a modified opposite double-jet air curtain (ODAC) that under the same supply air volume and HRR the carbon monoxide (CO) concentration with the ODAC is clearly lower than that with a traditional air curtain.

Hybrid ventilation is defined as the combination of natural ventilation and mechanical ventilation, and has often been used for energy saving [14–18], but rarely for fire-induced smoke control. One of the findings is the Gao's simulation study on a subway station firing [19] that hybrid ventilation had an effect on smoke dispersion when mechanical ventilation worked well with natural ventilation through roof vent.

In this paper, for a large single space firing, two hybrid ventilations are proposed that natural ventilation through a roof opening are combined with mechanical jet flow or with mechanical suction flow from sidewalls. Experiments were carried out to investigate the influences of jet flow or suction flow on smoke distributions. Also, sensitivity analyses are done with simulations to find out the influences of opening area ratio, fire source, and inlets/outlets on mass flow rates of the roof opening, maximum temperatures and CO concentrations, and fire plume.

2. Model experiment

2.1. The physical model

The prototype building is with size of 24 m (W) × 20 m (H) × 28 m (L). The experimental model was reproduced as the 1/10 of the prototype. The walls and ceiling were made of fire-proof plate. Two doors with each size of 0.3 m (W) × 0.25 m (H) were located at two opposite walls in width. A horizontal roof opening was set in center of the ceiling to achieve natural ventilation, and its size can be adjustable by moving its cover plate. A tempered glass window with 1.4 m (W) × 2 m (H) was set at one wall in length to facilitate observing the fire smoke spreading. Eight round vents with each diameter of 0.1 m were evenly installed on one wall in width, and its heights above the ground were equal and adjustable in range of 0.2 m through a movable plate. The same arrangement was on the opposite wall. Vents on each wall were equally divided into two groups, and every four vents in one group were piped together and driven by an inverter axial fan. The experimental rig is shown in Fig. 1 (a) and (b).

5 groups of thermocouple trees made of iron were placed in the experimental model. One group was arranged horizontally under the ceiling, and 15 thermocouples were evenly fixed on it and denoted by a1-a15 in order to measure the ceiling temperatures; another horizontal group was 0.2 m high above the ground, and 7 thermocouples were evenly fixed on it and denoted by b1-b7 so as to measure the occupied zone temperatures; the other 3 groups were all vertically, and every 5 thermocouples were fixed on one group and denoted by c11-c15, c21-c25, c31-c35 respectively. Such arrangements were depicted in Fig. 1(c). All thermocouples were connected into an Agilent34970A data acquisition unit and the response time was on the order of 10 s.

2.2. Fire source

A pool fire's heat release rate, Q (kW) is given by the following [20]:

$$Q = A_f \cdot m^{'} \cdot x \cdot \Delta H_c \tag{1}$$

Where A_f (m^2) is the horizontal burning area of the fuel; m' (g/s/m^2)

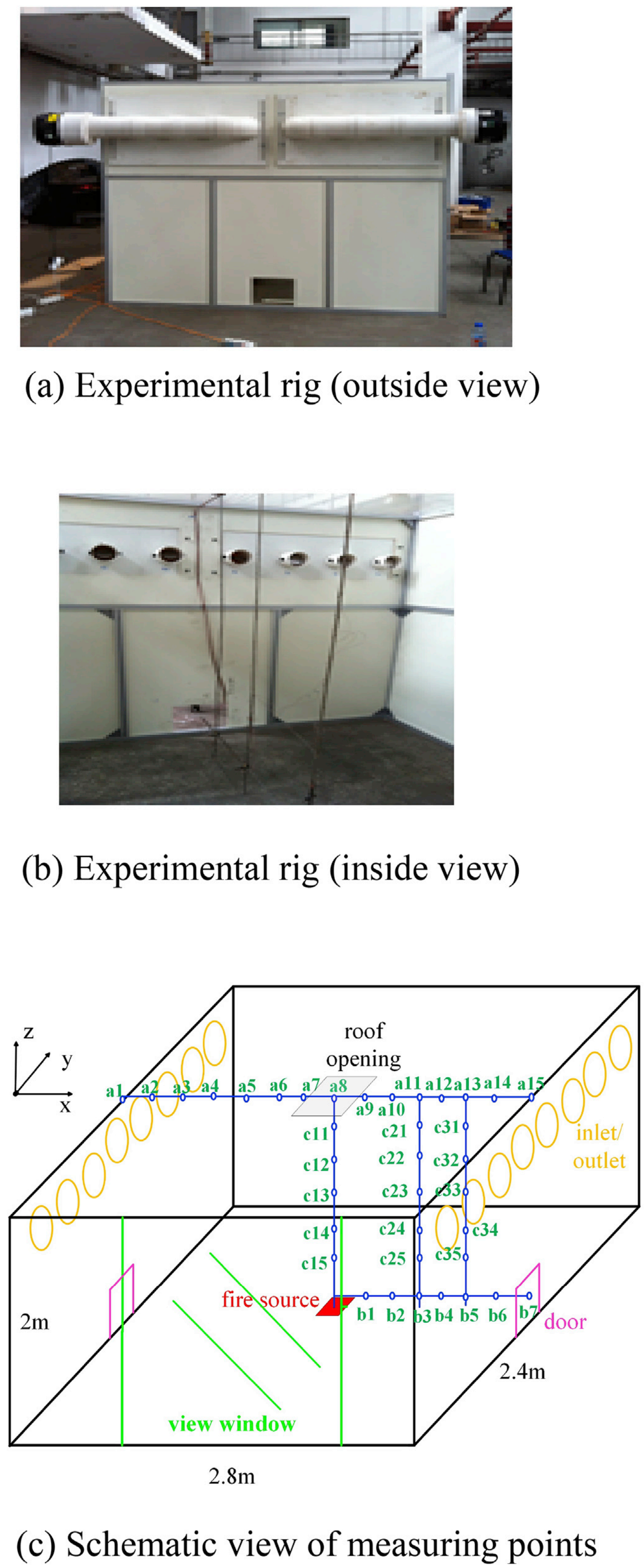

Fig. 1. Design of experimental apparatus.

is the average burning rate per unit area; x (%) is the combustion efficiency; $\triangle H_c$ (kJ/g) is the combustion heat. Alcohols, such as methanol and ethanol, burn with a flame that is hardly visible, indicating that very little soot is produced; hence, it has a combustion efficiency x close to unity. Several oil pans with each size of 7.5 cm (L) × 7.5 cm (W) were