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PRELIMINARY STUDIES ON MECHANICAL SMOKE EXHAUSTS IN LARGE SPACE BUILDING FIRES

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ABSTRACT

An analysis of the requirements for mechanical smoke exhaust in large space buildings was made and some experiments in a fire test atrium have been performed. It can be concluded that the temperature of smoke in large space building fire is usually quite low which makes them easy to descend and to mix with air. Usually it's difficult to control the descending of a smoke layer effectively when there is a fire source. Mechanical smoke exhaust is an exchange process of smoke and air. It clears smoke away mostly by dilution. The influence of fans to disturb flow fields and the location of air supply openings should also be taken into account.

Keywords: Large buildings, smoke control, mechanical smoke exhaust, air supply.

INTRODUCTION

In a building fire, smoke is the most harmful element to the occupants because of its toxicity, obscuration and high temperature. Smoke is more harmful in large space buildings, such as atriums, as the fire and smoke compartmentation can't be effectively applied there. Smoke easily endangers neighbouring floors or rooms once it spreads to the atrium. In order to decrease the menace to occupants, some measures should be taken to control the smoke descending in buildings. Thus, the occupants can be evacuated to safe places before the smoke falls to the dangerous height. This is important for safe evacuations.

In building fires, a mechanical fan is usually used to extract the smoke. It is the most effective method for controlling smoke. The studies on smoke exhaust in buildings are generally based on the zone model. Namely, there are two zones in the building, i.e., upper hot smoke zone and lower cool air zone. If the fans are installed on the top of the building, and if its exhaust rate is larger than the smoke production rate, the smoke would be controlled at the safe height. But for a large space building, the smoke temperature will decrease quickly, so the buoyancy reduces. Thus, the smoke easily descends and mixes with air, affecting the exhaust efficiency. There are few studies on these concepts, with almost no data on full-scale experiments.

For further studies on the characteristics of smoke evacuation in large buildings, a full-scale fire test atrium was constructed by USTC and PolyU (Figure 1) to conduct mainly atrium fire experiments. Its inner size was 22.4 m (long) ×1 1.9 m (wide) × 27.0 m (high). Eight vents were left on the roof, with four of them having HTP-II-11 smoke exhaust fans installed. A series of experiments have been performed. This paper introduces some mechanical smoke exhaust experiments. The smoke temperature, exhaust efficiency and the supplied air rate are discussed.

THEORETICAL ANALYSIS ON MECHANICAL SMOKE EXTHAUST

In the process of mechanical smoke exhaust, the smoke producing rate and the exhaust rate determines the variation of the smoke layer thickness. If the smoke exhaust rate is larger than the smoke producing rate, the smoke layer will not descend. Otherwise, smoke will descend gradually. The smoke layer is kept at a height when the exhaust rate is equal to the smoke producing rate. The smoke producing rate can be determined by the air entrainment rate to the plume. The mass conservation equation of a smoke layer in mechanical smoke exhaust is presented as follows:

$$\frac{\mathrm{d}[A\rho_s(H-Z)]}{\mathrm{d}t} = \dot{m} - \dot{m}_e \tag{1}$$

where Z is the smoke interface height, $\dot{m}$ is the mass rate of air entrained by the smoke plume at the height of Z, $\dot{m}_e$ is the mechanical smoke exhaust rate, H is the height of building, A is the cross-section area, ρ_s is the smoke density. For large space buildings, the plume can usually be thought of as axisymmetric. Based on Zukoski's study, the mass entrainment rate of this plume can be expressed as:

$$\dot{m} = 0.21\left(\frac{\rho_a g}{C_P T_a}\right)^{1/3} Q_c^{1/3} Z^{5/3} \tag{2}$$

The smoke exhaust rate can also be written in terms of volume flow rate $\dot{V}_e$ as:

$$\dot{m}_e = \dot{V}_e \rho_s \tag{3}$$

As the smoke density varies little, it can be considered a constant. Substituting Equations 2 and 3 into Equation 1, the differential equation of smoke layer height with time can be obtained:

$$-\frac{\mathrm{d}Z}{\mathrm{d}t} = 0.21\left(\frac{\rho_a g}{C_p T_a}\right)^{1/3} \frac{Q_c^{1/3} Z^{5/3}}{A\rho_s} - \frac{\dot{V}_e}{A} \tag{4}$$

If the smoke layer is required to be kept at a certain height, the smoke exhaust rate should be equal to that of plume entrainments. Therefore, the required mechanical smoke exhaust rate is approximately:

$$\rho_s \dot{V}_e = 0.21\left(\frac{\rho_a g}{C_p T_a}\right)^{1/3} Q_c^{\,1/3} Z^{5/3} \tag{5}$$

The density of smoke layer ρ_s can be solved by state equation:

$$\rho_s = \rho_a T_a / T \tag{6}$$

The temperature of the smoke layer T can be obtained by the energy equation:

$$T = T_a + Q_c / C_p \dot{m} \tag{7}$$

Hence, the mechanical smoke exhaust rate for keeping the smoke layer at a certain height should be:

$$\dot{V}_e = 0.21\left(\frac{g}{C_p \rho_a^{\,2} T_a}\right)^{1/3} Q_c^{\,1/3} Z^{5/3} + \frac{Q_c}{C_p T_a \rho_a} \tag{8}$$

The basic premise of this model is that the smoke temperature is high to form a steady upper smoke layer. For common building fires, it has been shown by many experiments that the smoke temperature in a fire room is around several hundred degrees Celsius. The smoke can easily be buoyed under the ceiling. But in large space buildings, smoke presents a much lower temperature than that in common buildings. Smoke can be mixed with lower temperature air as its buoyancy is not high. So the rationality of Equation 8 needs to be further validated.

EXPERIMENTAL ARRANGEMENT

Figure 2 shows the arrangement of the test system. On the roof of the Atrium, there were 8 vents of size 1.2 m × 1.2 m. Four mechanic exhaust fans were installed, at vents of 1, 4, 5, and 8. The fans diameters were 1.1 m. The exhaust rates of three fans were fixed at 50000 m^3/h, and the other one was adjustable up to 50000m^3/h. Therefore, the total smoke exhaust rate was adjustable up to 200000 m^3/h. The volume of the Atrium was about 7200 m^3, the maximum air replacement rate could reach 27 times/h. In each floor, there were 11 windows of size 1.5 m × 1.2 m. The windows in the lower floors and the curtain door could be set as air entrances.

Diesel oil was used as the fuel. Two oil pool sizes were used: 1 m × 1 m and 0.5 m × 0.5 m. In order to keep the oil surface smooth, the large pool bottom was paved with fireproof clay. Circulating water cooled the smaller pool bottom. Using oil as the fuel allowed the flame to spread all over the surface in several seconds, so the fire can be thought of as steady. In all these experiments, the pool was placed in the center of the Hall. Smoke temperature was obtained through two T-type thermocouple trees hung vertically under openings 2 and 8. The former tree contained 18 thermocouples with an interval of 1.5 m. The latter had 10 thermocouples with an interval of 2 m. In order to discern the smoke layer height by video camera and eye, an indicating rope with 12 marking lamps at intervals of 2m was hung near the eastern wall.

The experiments concentrated mainly on the growth of smoke in the process of mechanical smoke exhaust of pool fires in large space buildings. As prescribed in the "Code for fire protection design of tall civil buildings" GB 50045-95, when an atrium volume is less than 17000 m^3 the air exchange rate should be larger than 6 times per hour. If the volume of the Atrium is about 7200 m^3 following the above air exchange rate, the smoke exhaust rate will be 7200 × 6/3600 m^3/s. This series of experiments were undertaken with an exhaust rate of 28 m^3/s.

RESULTS AND DISCUSSION

The basic conditions of the experiments are listed in Table 1. The process of the smoke exhaust experiment can be divided into three main stages: (a) from ignition to fans running normally. This is the preparation stage before exhaust. The time of this stage is short, while it includes the time of the plume rising to the ceiling, the time of the smoke layer forming, the time for smoke to descend, the fan startup and the time for the fans to run normally. The smoke layer height for fan startup was set at 17 m. (b) from fans running normally to fire extinguishment. This is the main stage for studying the smoke control by fans. In ideal situations, the hot smoke will rise into the smoke layer with some rate. If the fans with larger exhaust rates were installed on the roof, the smoke can be controlled at some height to avoid its hazard to the occupants in lower floors. But the difference between real and ideal situations needs further validation. (c) from fire extinguishment to stopping exhaust. This is the follow-up smoke exhaust stage. Details on the experimental results follow.

The variation of the smoke temperature

Figure 3 illustrates the variation of smoke temperatures in the experiment. The icon *Ti* represents the temperature at the height of *i* meters. The first stage lasted about 75 s. In this stage, the responses of the two thermocouple trees were nearly the same. Those above 20 m responded quickly, and other responses were not obvious. The temperatures showed little difference, but temperatures near the ceiling were the highest. The second stage lasted about 150 s. It can be seen from the two figures that the temperatures have a slow and short rising period. The cool air was entrained into the smoke. This leads the temperature to rise slow transitorily. With the burning continuing, temperatures kept rising. But at this stage, the temperature near the ceiling (27 m) was not the highest. This could have resulted in heat emission from the ceiling. The lower thermocouples also responded in turn, this shows the smoke reached the corresponding positions. In Figure (b), the temperatures at 17 m and 15 m rose more quickly than that in Figure (a). This shows the effect of the fan. The thermocouple tree in (b) was hung beneath a ventilation fan, leading the smoke to this position, and making the smoke temperature rise. It is also shown that the largest temperature rise was only 25^{0}C.

The height of the smoke layer

Since the temperature of the smoke is low, the buoyancy is not very strong. After smoke rises to 20 m, the rising velocity becomes quite slow. Some smoke will disperse even before reaching the ceiling. The phenomenon is much clearer when the fire's power is smaller. At the initial stage of burning, smoke will fall even when it doesn't rise to the ceiling. After an initial smoke layer forms, a relatively clear interface will appear. It indicates that some errors will be obtained when using two-zone fire models to describe the smoke layer in the Atrium during the initial period of burning. The two-zone model only applies when the initial smoke layer develops fully.

Figure 4 shows the development of the smoke layer height with time. The startup condition of the fan is when the smoke layer thickness reaches 10 m, namely the smoke layer height is 17 m. It took some time for the fan to go from startup to running normally, at which time the smoke layer height was about 16 m. It can be seen from this figure that the smoke descends quickly at this height. There are two reasons for the phenomena. One is that the indicating lamps for observing the smoke layer height were near the fan, and the smoke migrates to the area under the fan. Thus, the smoke in this area increases. The other is that the fan attracts air into the smoke layer. The mixing of smoke and air also leads to the smoke volume increasing. After some time, the smoke descends more slowly. This shows the smoke exhaust has some control effect on the descending smoke. But it can also be seen that the smoke still descend to near the floor. The exhaust by fans could not control the smoke completely under the current exhaust rates.

Effects of air supply rate on the test

In order to exhaust smoke effectively, enough fresh air should be supplied into the Atrium while exhausting. There are several effects of the supplied air. Firstly, it can provide air for the fire. Secondly, it can prevent the smoke layers descending. Thirdly, it will mix with the smoke and make the temperature and density of the smoke decrease quickly. The area, distribution, and height of air supplied openings are the key parameters affecting the effectual exhaust. Without supplying enough area, the supplied air **rate will** be less than the exhaust smoke rate. The effect of supplied air with a large opening and several small openings will be different.

Three situations of air supplied openings were adopted in the experiments to compare the influence of supplied opening area and height: (1) the curtain door on the ground floor. Adjusting the opening height of the door, the air supply area can be changed, (2) the windows of the ground floor. The air supplied area can change through adjusting the quantity of windows, (3) the windows around the first floor. The bottom of the windows was 5 m above the ground.

Figure 5 shows the flame shape when the air is supply through the curtain door. The opening door height was 1.8 m, so the air supply open area was 7.2 m^2. The distance from the fire to the door was about 5 m. The supplied air could reach the fire quickly. The fan started 70 s after ignition. It can be seen from Figure 5 that the flame was deflected several seconds after fan startup, and a large intermittent flame jumped from the fire frequently. The fire area increased. This shows clearly that it will hasten the burning if the supplied opening is near the fire.

Figure 6 shows the fire situation when the ground floor windows are set as air supply openings. Four windows on its eastern wall were opened at the same time, the supplied air was distributed, and there was no strong unidirectional flow. The bottom of the windows was 1.5 m above the floor, so only the flame top was affected lightly.

Figure 7 shows the flame photos when air was supplied from the windows of the first floor. The supplied air was higher than the flame, and the smoke moved upwards. It is not easy for the supplied air to access the fire source. So the supplied air has hardly any influence on the flame's shape.

The mechanical fan could only delay the descending smoke. Generally, the smoke could descend down to 1 to 2 m above the air supply opening. But under the effect of supplied air, the smoke surface was not smooth. The smoke in the area where it is just a "head-above" the air supply opening can be diluted significantly. When the air is supplied through unilateral windows, the upper smoke can descend along the wall opposite the supply opening. When the windows are on the ground floor, the smoke can descend down to near the ground. The air supplied through these openings can't effectively prevent the smoke at higher heights.

As seen from Figure 5, the curtain door and the test cabin located in the Atrium were blurry at 110 s. This indicates that the smoke had descended down to 4 m above the ground. It has affected the identification to the escape path. In Figure 6, at 110 s, the curtain door and the cabin were obscured. The effect of supplied air to control the smoke is not good. But in Figure 7, the door and the Atrium were still very clear at the same time. When the smoke descends to the height of 10 m, the supplied air can generally prevent it descending. This illustrates that the effect of air supplied from first floor windows is good.

Smoke dilution after fire extinguishment

After the fire was extinguished, the fans still ran to exhaust the remaining smoke. Since there was no smoke being produced, it should have been easy to empty the smoke. But the supplied air and smoke cannot be displaced entirely. Compared to the volume of the Atrium, the areas of supplied and exhaust openings were small, and the air could not drive the smoke to move wholly toward the exhaust openings. Also, the temperature difference between the air and the smoke was small, so they readily mixed. The exhaust smoke was the smoke diluted with air. So the emptying time was much longer than the time of displacing one room volume. In large space buildings, the mixing of air and smoke is very uneven. Near the supply openings, smoke is diluted quickly, while at the corners, smoke hardly flows, and the concentration of smoke changes slowly. If the air supply opening is close to the fan, the fresh air can be exhausted directly, mixing with little smoke. It is obvious that using distributed air supply openings is helpful in preventing smoke accumulation in some regions.

Usually, the smoke temperature was still higher than that of the air long before the fire was extinguished. Most of the smoke was still buoyant. So during the exhaust process, the lower smoke dilutes more quickly, and the upper smoke more slowly. An indistinct region, dividing the thick smoke and the thin smoke, could be identified. But this shouldn't be taken as a clear interface of smoke and air.

It should be noted that if the locations of air supply openings are higher, the temperature of smoke below these openings would decrease more quickly and the smoke will be detained at the lower regions. It is difficult to exhaust this smoke through the top fans. Using ground floor supply air is helpful to exhaust this smoke. Hence, the supplied air openings should be set lower so that the supplied air cannot enhance the burning.

CONCLUSIONS

The smoke movement in large space buildings with mechanical smoke exhaust was analyzed. Also, some mechanical smoke exhaust experiments were conducted in the USTC/PolyU Atrium. Results indicate that smoke temperature decreases quite notably in large space buildings. This kind of smoke readily descends. Mechanical smoke exhaust is an effective way to control smoke in large buildings. It can decrease the speed of smoke descending, and is good for lowering the concentration of smoke. But it was also shown in the experiments that the startup of smoke exhaust fans will disturb the flow fields greatly, and may cause some smoke and air to mix, which will influence the effect of smoke exhaust. It was impossible to completely extract the smoke within the time constraints of the experiments.

Appropriate mechanical smoke exhaust rates, positions of air supply openings, and rules for smoke movement in the period of exhaust are all areas needing further study.

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Table 1: The basic conditions of experiments.

Experiment No.	Pool size	Fuel mass	Burning time	Supplied air opens	Condition for fans' startup	Running fans
0309 - 2	0.25 m^2 with cooling water	6.1 kg	176 s	8 windows of first floor	Smoke layer thickness 10 m	No.2, 3
0309 - 3	0.25 m^2 with cooling water	6 kg	195 s	4 windows of ground floor rolling steel door 4 m×1.4 m	Smoke layer thickness 10 m	No. 1, 3
0430 - 1	1 m^2 without water or clay	6 kg	410 s	rolling steel door 4 m×1.4 m	Smoke layer thickness 10 m	No. 1, 3
0430 - 3	1 m^2 without water or clay	6 kg	348 s	4 windows of first floor	Smoke layer thickness 10 m	No. 1, 3
0516 - 1	1 m^2 with fireproof clay	6 kg	198 s	rolling steel door 4 m×1.4 m	Smoke layer thickness 10 m	No. 1, 3
0516 - 2	1 m^2 with fireproof clay	6 kg	190 s	4 windows of ground floor	Smoke layer thickness 10 m	No. 1, 3
0525 - 2	1 m^2 with fireproof clay	6 kg	208 s	8 windows of second floor	Smoke layer thickness 10 m	No. 1, 3

Figure 1: Out View of the USTC/PolyU Atrium.

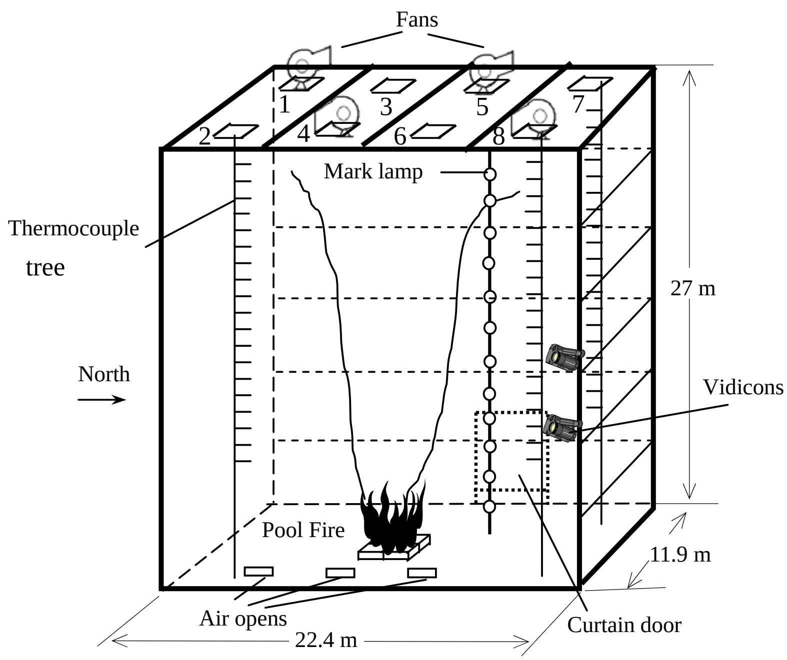
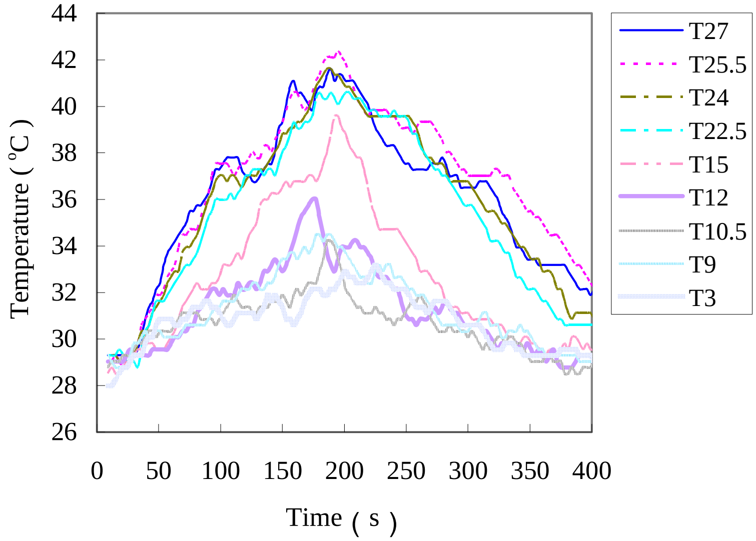
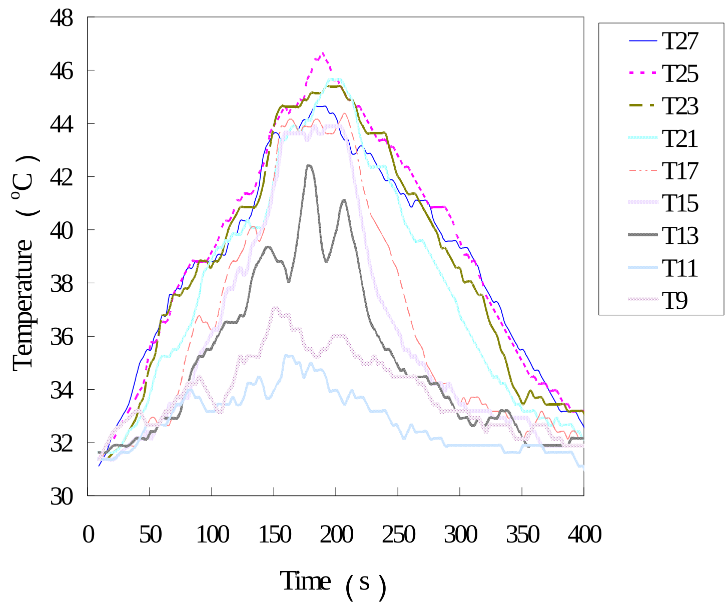


Figure 2:. Sketch of experiment arrangement.



(a) measured with the thermocouple tree under vent 2.



(b) measured with the thermocouple tree under vent 8.

Figure 3: The vertical temperature distribution in the Atrium.

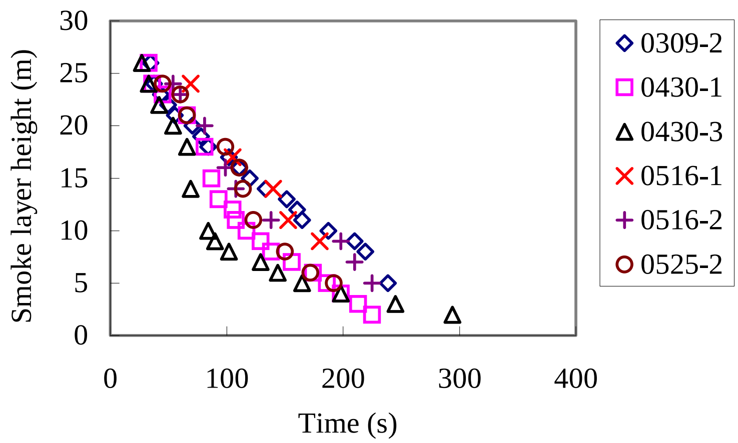


Figure 4: The development of smoke layer height with time.

30s after ignition

60s after ignition

80s after ignition

110s after ignition

Figure 5: The flame shape when air is supplied through the rolling steel door.

30s after ignition

60s after ignition

80s after ignition

110s after ignition

Figure 6: The flame shape when air issupplied through ground floor windows.

30s after ignition

60s after ignition

80s after ignition

110s after ignition

Figure 7: The flame shape when air is supplied through the first floor windows.