SMOKE MOVEMENT IN OPEN SPACE IN SHOPPING MALLS

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ABSTRACT

A number of fires were reported in large shopping malls in China in recent years. In view of this, smoke flow in a large open retailing space inside a shopping mall with a relatively low ceiling was studied. Full-scale burning tests with five different scenarios were carried out to study the natural smoke-filling process and mechanical smoke exhaust. The distributions of temperature, carbon monoxide, carbon dioxide and oxygen were also measured. Results indicated that under mechanical exhaust with make-up air, the two-layer zone model is still suitable for application. The value of 0.5 m height for the vertical wall for blocking smoke commonly used in shopping malls is not very effective in preventing smoke spread. By adjusting the height of the vertical wall and adopting the smoke extraction rate of 60 m^3h^{-1} specified in the Chinese fire code, smoke produced from a 3 MW fire can be confined in the smoke zone.

1. INTRODUCTION

Accidental fires occurred in large shopping malls in recent years in China indicated that smoke is the major reason for casualties. Toxic gases such as carbon monoxide (CO), carbon dioxide (CO_2), hydrogen chloride (HCl) and hydrogen cyanide (HCN) in smoke generated from fires would cause suffocation. Smoke will also reduce the visibility of the occupants inside. When a fire occurs, smoke will spread much faster than heat. Therefore, smoke movement is an important topic in fire science.

Smoke movement will be affected by the building geometry. Now, it is common to have large and open retailing space in shopping malls. There is a relatively low ceiling (height of 3 to 4 m) but with a larger floor area. Large amounts of combustible goods are stored in this type of open space. Without compartmentation, smoke can spread quickly in a fire. There had been some investigational works carried out on smoke management in atrium buildings with a high ceiling, but relatively not so many studies on large shopping malls having a low ceiling and large open space for retailing. A series of experiments were carried out in a modelled underground shopping centre in the Tianjin Fire Research Institute, China. The objectives are to study preliminarily the smoke-filling process, smoke spreading, mechanical smoke extraction systems and also the effect of make-up air on the efficiency of the system.

2. EXPERIMENTAL SET-UP

Experiments were carried out at the first level of a scaled model of a shopping centre constructed at the Tianjin Fire Research Institute. The experimental space has an area of about 300 m^2 (19.5 × 15.5 m), a ceiling height of 3.7 m, and two curtained doors to outside as shown in Fig. 1.

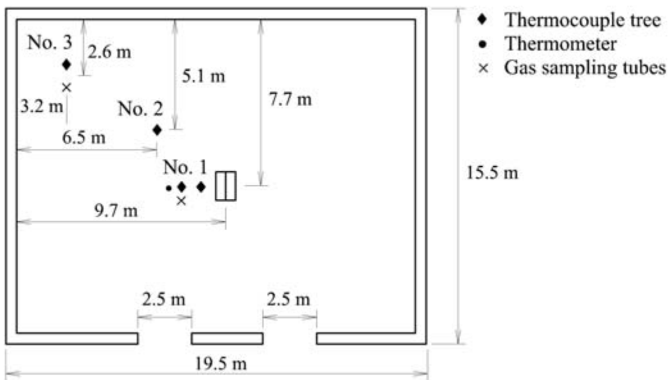


Fig. 1: Experimental hall

Mechanical smoke extraction system was installed with six extraction vents of size 0.63 m by 0.63 m distributed uniformly in the ceiling. The vents were connected to the main exhaust duct through two sub-ducts, and the main duct was connected to an extraction fan, which has an extraction rate of 44,128 m^3h^{-1}. The extraction rate can be adjusted to satisfy the demand of 60 $m^3m^{-2}h^{-1}$ as specified in the standard by adjusting the degree of opening the butterfly valve on the main exhaust duct and the valve at the blower of the extraction fan.

In the experiments, cardboard boxes of 0.47 m × 0.47 m × 0.35 m with Acrylonitrile, Butadiene and Styrene (ABS) boards and polystyrene foam (PSF) plastics inside were piled up and used as the fire source. These actually simulated the packaged domestic electrical appliances for sale in large shopping malls. Burning such objects can simulate the initial development of a fire started in a large underground shopping centre. Those cardboard boxes were piled up to 1.41 m × 0.94 m on a wooden bracket. The total weight of the combustibles was 67 kg, with 23.4 kg of cardboard boxes, 23.4 kg of ABS boards, 13 kg of PSF and 7.2 kg of wooden bracket.

3. EXPERIMENTAL CONDITIONS

Large and open retailing space in underground shopping centres is usually divided into zones separated by smoke screens, roof beams or other structures which can block the spreading of smoke. When the extraction fan operates, air will flow into the room of fire origin from under the smoke screen to displace the smoke being extracted out. This, to a certain extent, will have some effects on preventing the spreading of smoke.

With the same fire source, three scenarios were considered:

- Scenario 1

  Natural smoke-filling without smoke extraction. The mechanical smoke extraction system is not operated and the two curtained doors to outside are closed. This is the worst case compared with the other two scenarios.

- Scenario 2

  Mechanical smoke extraction only without make-up air. The system is operated 1 min after the source is ignited. The two curtained doors to outside are closed.

- Scenario 3, 4, 5

  Mechanical smoke extraction with make-up air from under the curtains. The system is operated 1 min after the source is ignited and the two curtained doors to outside are raised to a certain height to allow entering of make-up air.

Experiments were carried out under the conditions with the curtain edge at 1.2 m, 1.6 m, 2 m, and 3.2 m (the curtain edge is 0.5 m from the ceiling) above the floor level. The smoke extraction rate 60 $m^3m^{-2}h^{-1}$ as specified in the current Chinese Fire Code was adopted in all the experiments with mechanical smoke extraction in this study. The curtains were also raised to different heights for observing the effectiveness of smoke blocking and the effect of make-up air on it.

4. PHYSICAL VARIABLES AND MONITORING POSITIONS

- Rate of mass loss in combustion

  Throughout the experiments, the piles of cardboard boxes simulating packaged domestic electrical appliances were placed on a weighing table. There is a sensor on each of the four legs of the weighing table, which can detect the variations in mass throughout the combustion process, and then transmit the data to a computer data acquisition system. From the curves of the rate of mass loss, the mass of combustibles burnt in each second can be calculated, such that the variations of the rate of heat release during the combustion process can also be estimated.

Table 1: Descriptions of different scenarios

Scenario	Descriptions
1	Natural smoke-filling without smoke extraction
2	Mechanical smoke extraction only without make-up air
3	Mechanical smoke extraction with make-up air from under the curtain raised by 1.2 m
4	Mechanical smoke extraction with make-up air from under the curtain raised by 1.6 m
5	Mechanical smoke extraction with make-up air from under the curtain raised by 2 m

- Temperature Distribution

  Temperature is the main variable reflecting the changes in an indoor fire environment. In this study, three thermocouple trees were placed at different positions to measure the vertical and horizontal temperature distribution, as well as the temperature distribution near the fire source. There were eight thermocouples on the thermocouple tree near the fire source, and 11 thermocouples on each of the other two thermocouple trees. Thermocouples on each thermocouple tree were positioned at intervals of 0.3 m starting from 0.05 m below the ceiling.

- Gases Composition and Concentration (O_2, CO, CO_2)

  Toxic gases in smoke are the main cause of deaths in fires. Therefore, the concentration of toxic gases in smoke is one of the variables of much concern. Two gas sampling tubes were placed in a position near the fire source and another position far away from the fire source. Each sampling tube has two gas sampling probes, one at 0.15 m below the ceiling and the other one at 1.5 m above the ground. In that way, the concentrations of O_2, CO, CO_2 at the upper smoke layer and the lower air layer at different positions in the room were measured.

5. OBSERVATIONS

After ignition of the fire source, the piles of cardboard boxes simulating packaged domestic electrical appliances started to burn, and a fire plume was formed. When it reached the ceiling, the flow changed in direction and spread radially. In this experimental space, the time required for the smoke to spread to the edge of the zone was quite short of value within 20 s. The flow then changed direction again when the smoke front was blocked by the protected structure, giving a downward opposite jet. At the same time, this jet experienced the effect of buoyancy and moved upwards again after descending some distance. An early smoke layer was formed under the ceiling. As the fire grew, the smoke layer grew thicker with the smoke layer interface kept on descending.

A clear interface between the upper smoke layer and the lower air layer was observed in all the above experiments. Under the situations of natural smoke-filling without smoke extraction, and operating the mechanical smoke extraction system only without make-up air, the smoke layer interface was very vivid and stable. When operating the mechanical smoke extraction with make-up air, the effects from both mechanical smoke extraction and the make-up air made the smoke layer interface fluctuate, but the smoke layer was not destroyed. The interface was still very clear and two obvious layers were observed in the room.

6. VARIATIONS OF RATE OF MASS LOSS OF THE FIRE SOURCE

The curves of rate of mass loss of the weighing table under different scenarios are shown in Fig. 2. Since the mass of the weighing table varied slightly for each experiment, the starting point of each curve differed slightly. From the figure, it can be seen that the patterns of variations of rate of mass loss under different scenarios are basically similar, the maximum rate of heat release obtained from the curves was about 3 MW.

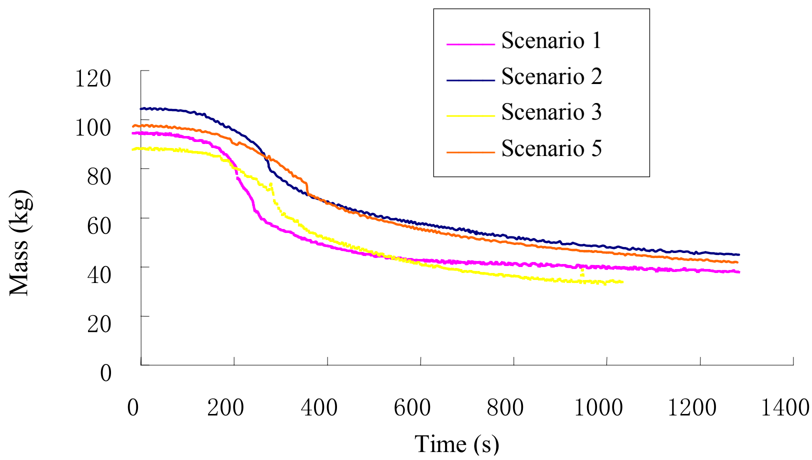


Fig. 2: Rate of mass loss of fire source under different scenarios

7. VARIATIONS OF SMOKE LAYER INTERFACE HEIGHT

The smoke layer interface height can be obtained by using the temperature measured by the thermocouple tree to estimate the interface height history against time by the principle of N%. At the same time, a ruler was put into the experimental space for visual observation of the descending of the smoke layer interface. The curves of the variations of smoke layer interface height under all scenarios are shown in Fig. 3. From the gradient of the curves, it can be seen that the smoke layer descended the fastest under natural smoke-filling. The descending was slower for the case with mechanical smoke extraction without make-up air, and even slower for the case with make-up air. It is because when the curtained door was opened, air would enter into the space by displacement, smoke extraction could be carried out smoothly. This demonstrated the important impact of make-up air on the effectiveness of smoke extraction. The rates of descending of smoke layer interface were similar for the cases with the curtain raised to 1.2 m, 1.6 m and 2 m.

In the experiments on mechanical smoke extraction with make-up air, when the curtain was raised to 3.2 m, i.e. the lower edge of the curtain for blocking smoke was at 0.5 m from the ceiling (the minimum distance specified in the standard), the smoke front flowed out of the experimental space rapidly from under the curtain edge after reaching it. When the curtain was raised to 2 m (at 1.7 m from the ceiling), the smoke layer interface descended gradually to under the curtain edge as the fire grew, with a small amount of smoke flowed out of the fire room. When the curtain was raised to 1.6 m (at 2.1 m from the ceiling), smoke did not flow out of the fire room throughout the experiment; the lowest position where the smoke layer descended levelled with the curtain edge. Under the flow of make-up air towards the fire room, smoke was being blown back to the fire room. This indicated that the airflow by make-up air has a certain effect on preventing the outflow of smoke. When the curtain was raised to 1.2 m (at 2.5 m from the ceiling), the smoke layer was kept above the curtain edge throughout the experiment.

8. VERTICAL TEMPERATURE DISTRIBUTION

The maximum temperature recorded and the time to reach it were different under different scenarios. The vertical temperature distribution under different scenarios as measured by all thermocouples on the same thermocouple tree No. 1, when the thermocouple nearest to the ceiling reached the maximum temperature, are given in Fig. 4.

As seen in Fig. 4, the vertical temperature distributions at a particular time under different scenarios as measured by thermocouples on the same thermocouple tree showed a similar trend. Higher temperature rise was observed for thermocouples nearer to the ceiling, and lower temperature rise for those closer to the ground. There are obvious turning points in gradient on each vertical temperature distribution curve. This indicated that the smoke layer interface was clear, and obvious changes in gradient were observed at the height near the smoke layer interface. As seen from the figure, the maximum temperature rise is the highest under natural smoke-filling without smoke extraction, followed by mechanical smoke extraction only without make-up air, and the maximum temperature rise is the lowest for the case of mechanical smoke extraction with make-up air. This is because when the curtain is opened, the extraction effect of the mechanical system led to displacement of large amount of outside air from under the curtain into the fire room. The heat and smoke was extracted out even more efficiently under both the cooling effect of the air displaced and mechanical smoke extraction. Therefore, compared with the situations without smoke extraction or without make-up air, the time to reach maximum temperature was delayed and the maximum temperature rise was reduced.

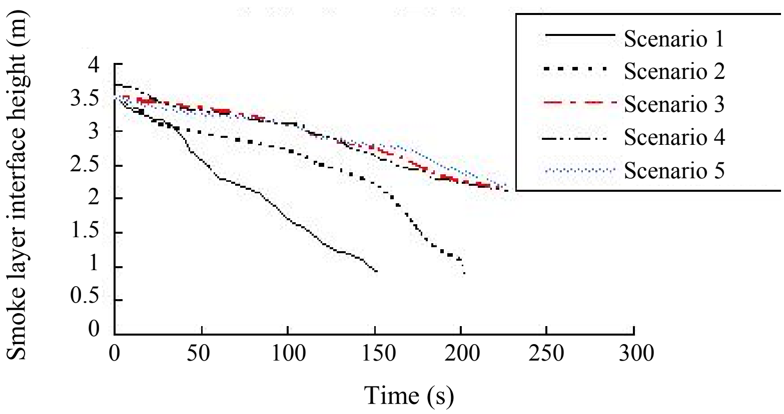


Fig. 3: Variations of smoke layer interface height under different scenarios

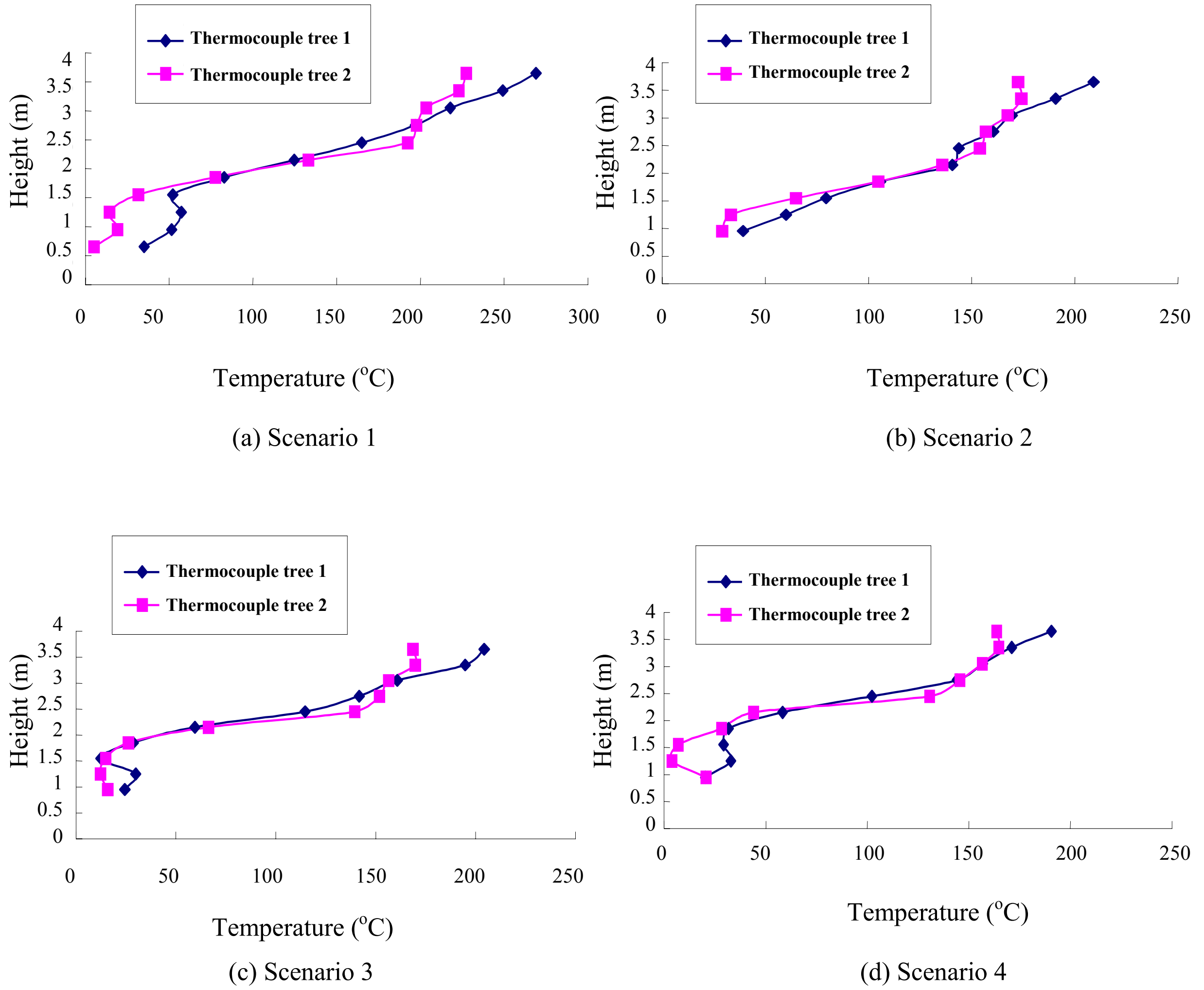


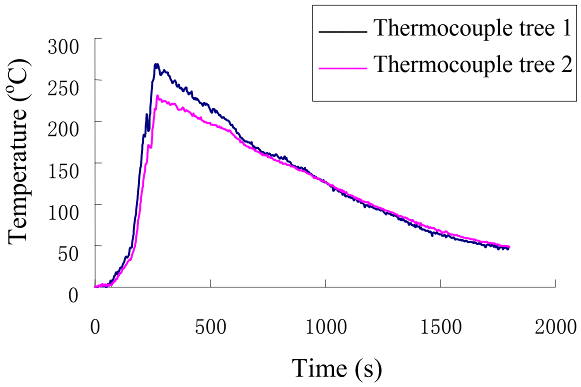
Fig. 4: Vertical temperature distribution

9. HORIZONTAL TEMPERATURE DISTRIBUTION (TEMPERATURE VARIATIONS OF DIFFERENT THERMOCOUPLE TREES)

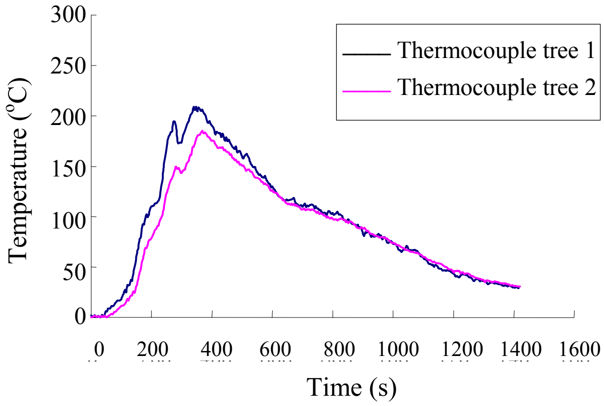
The temperature variations of the thermocouples nearest to the ceiling on thermocouple trees No. 1 and No. 2 at different distances away from the fire source are shown in Fig. 5. Despite all the temperatures measured by the thermocouple on thermocouple tree No. 2 were lower than that on thermocouple tree 1 which was closer to the fire source, the differences were small. The largest differences appeared when the maximum temperatures were reached, the smallest difference in percentage was 8.5 %, and the largest was 17.3 %. In all the experiments, the time to reach the maximum and minimum temperatures for the two thermocouples on two different thermocouple trees were almost the same. It indicated that to a certain extent, the assumption of uniform temperature in the upper smoke layer is practical.

10. VERTICAL DISTRIBUTION OF GASES CONCENTRATIONS (O_2, CO, CO_2)

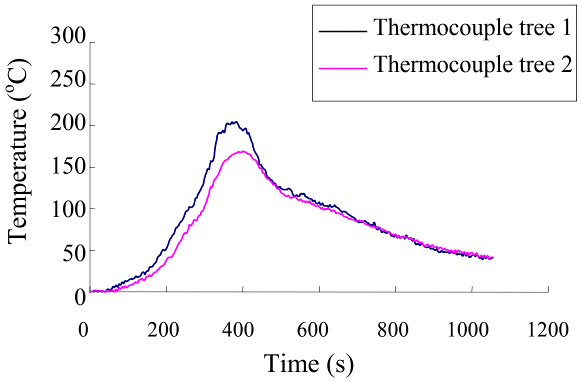
The variation curves of oxygen concentration measured by two gas sampling points on the sampling tube near the fire source under different scenarios are shown in Fig. 6. In the experiments with the curtain opened to allow air displacement while operating the mechanical smoke extraction system, the O_2 concentration was reduced slightly as measured at the sampling point at 1.5 m above ground. It indicated that the smoke layer was well stratified and did not enter the lower air layer, where the O_2 concentration was near to that of the ambient. Larger reduction in O_2 concentration was recorded at the sampling point 0.15 m below the ceiling and positioned inside the smoke layer. When compared with other scenarios, for the case of natural smoke-filling without smoke extraction, the reductions in O_2 concentration were larger not only at the sampling point nearer to the ceiling, but also at the sampling point 1.5 m above the ground, but the time to reach the minimum O_2 concentration at this sampling point was longer than at 0.15 m from the ceiling. It was also noted that under mechanical smoke extraction only without make-up air, the O_2 concentration also reduced at 1.5 m above ground. It demonstrated that smoke extraction is less effective without make-up air, smoke was not controlled at 1.5 m above ground in the experiment.



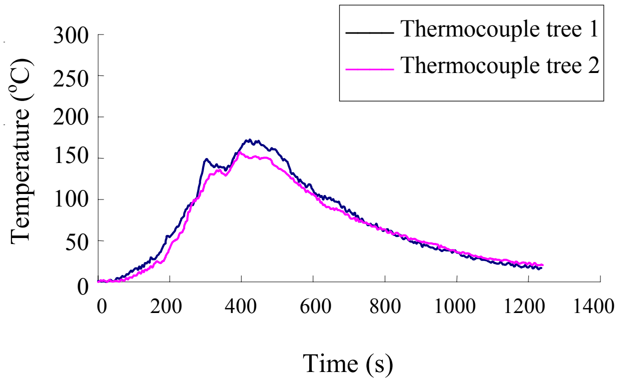
(a) Scenario 1



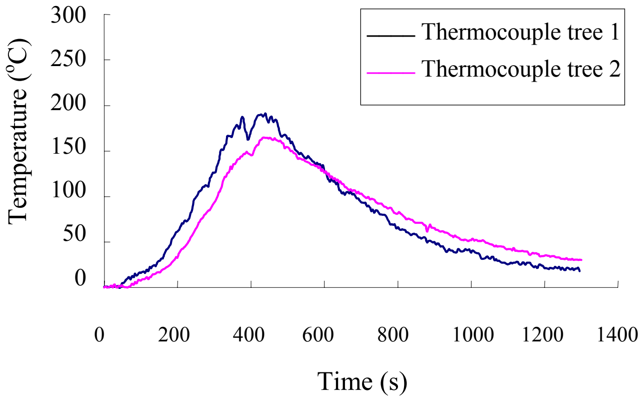
(b) Scenario 2



(c) Scenario 3



(d) Scenario 4



(e) Scenario 5

Fig. 5: Horizontal temperature distribution

The variation curves of CO_2 and CO concentrations measured by the gas sampling point at 0.15 m below the ceiling under different scenarios are shown in Fig. 7. When comparing the different scenarios, the maximum CO_2 and CO concentrations of 4.77 % and 0.11 % respectively were the highest under natural smoke-filling condition without smoke extraction; the extent of reduction in O_2 concentrations was also the largest, the lowest value was 15.77 %. Under mechanical smoke extraction without make-up air, the maximum concentrations of CO_2 and CO were comparatively lower, the reduction in O_2 concentrations was also smaller. For the three scenarios with mechanical smoke extraction and make-up air, the maximum CO_2 and CO concentrations were even lower, the reduction in O_2 concentration was the smallest. The results indicated that smoke extraction with make-up air can effectively delay the time for toxic gases to reach maximum values, and lower the concentrations of toxic products in the smoke layer and air layer.

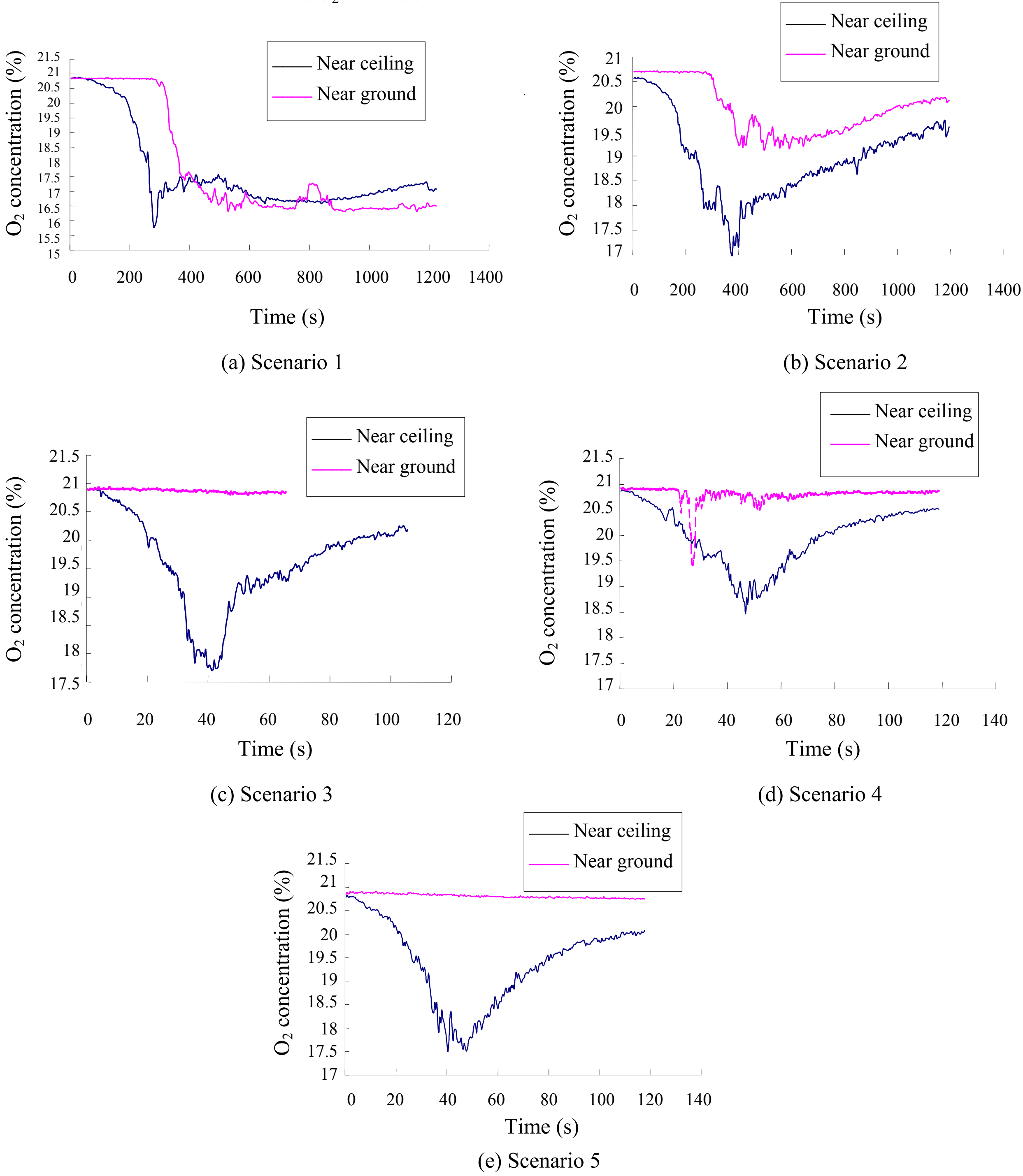
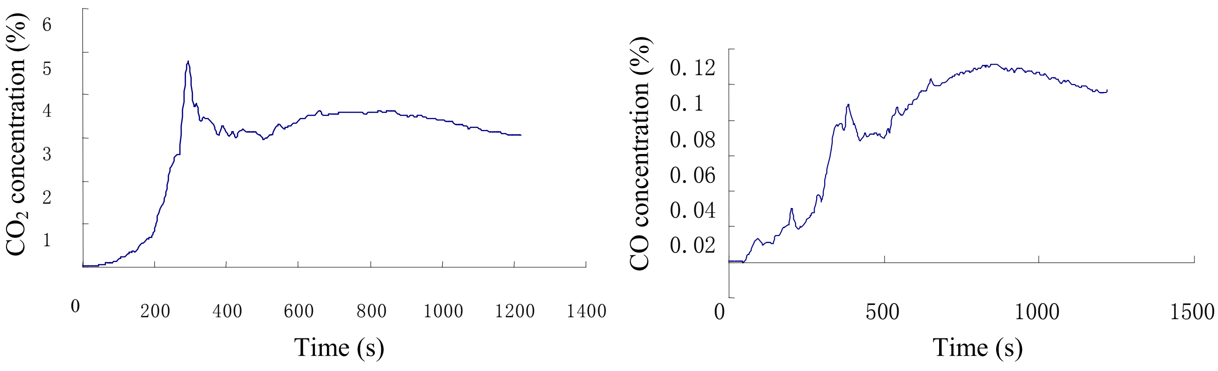
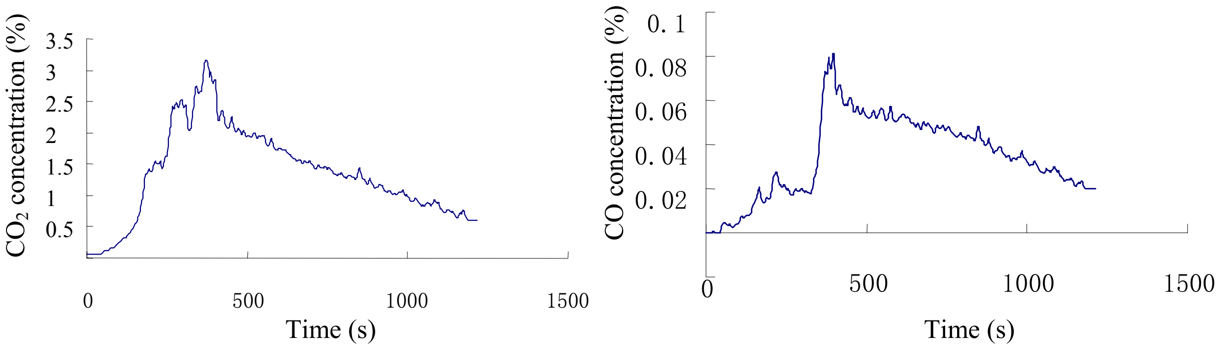


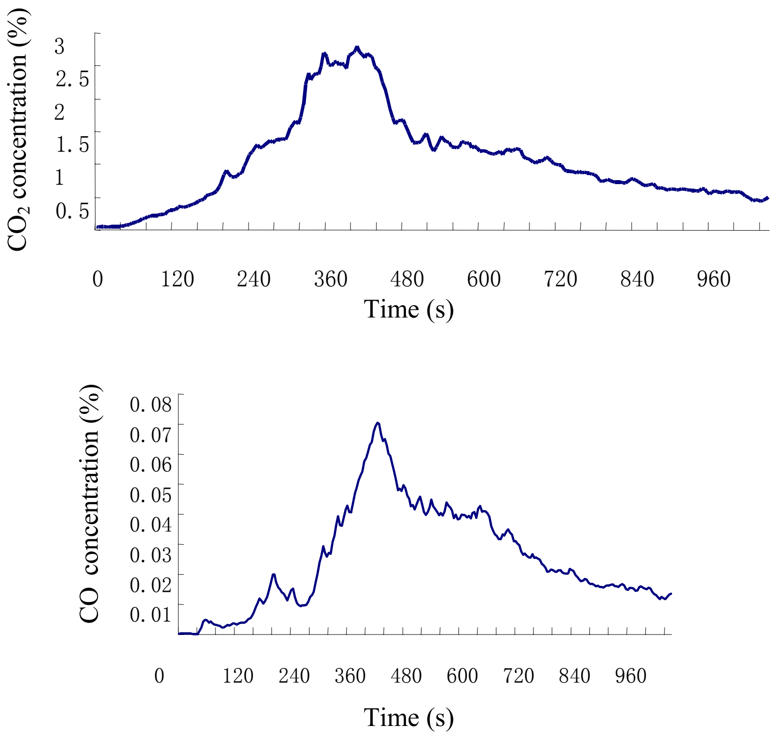
Fig. 6: Variations of O_2 concentration under different scenarios



(a) Scenario 1

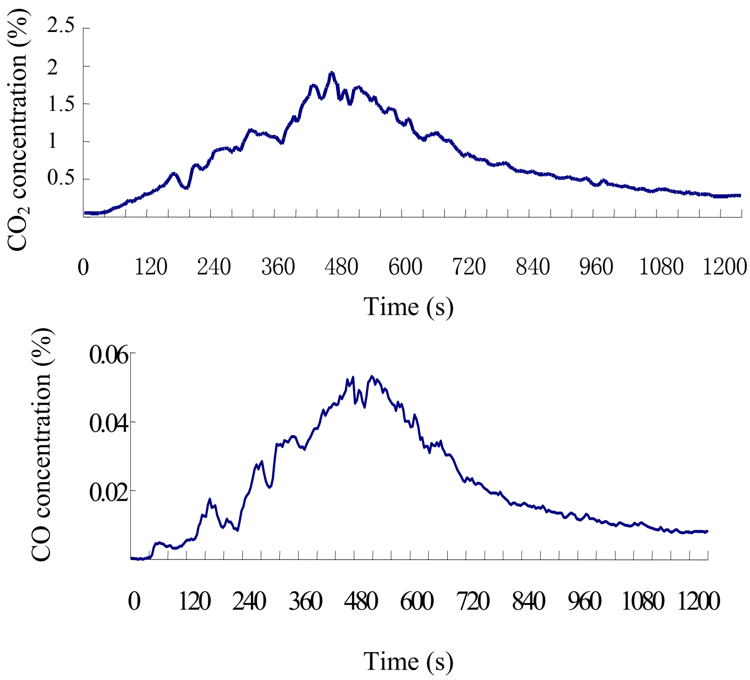


(b) Scenario 2

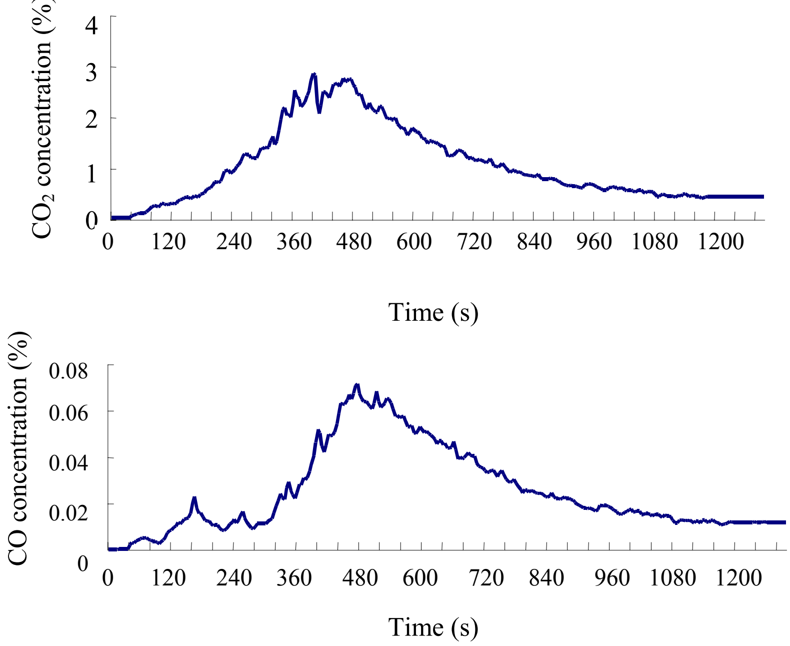


(c) Scenario 3

Fig. 7: Variations of CO and CO_2 concentrations under different scenarios



(d) Scenario 4



(e) Scenario 5

Fig. 7: Variations of CO and CO_2 concentrations under different scenarios

The time to reach the maximum values of CO_2 and CO, and the time to reach the minimum O_2 concentration under the five different scenarios are depicted in Fig. 8. The figure showed that smoke extraction with make-up air can effectively delay the rapid increase in toxic gases concentration and extend the time for escape.

As seen in Fig. 8, the time to reach the maximum CO and CO_2 concentration and the time to reach the minimum O_2 concentration showed an increasing trend from scenario 1 to 5, which clearly demonstrated the effectiveness of smoke extraction. However, the insignificant difference between scenarios 4 and 5 revealed that when air displacement took place to a certain extent, the mechanical smoke extraction system could effectively extract smoke, further improving the ventilation condition for air displacement would not further improve the effectiveness of smoke extraction.

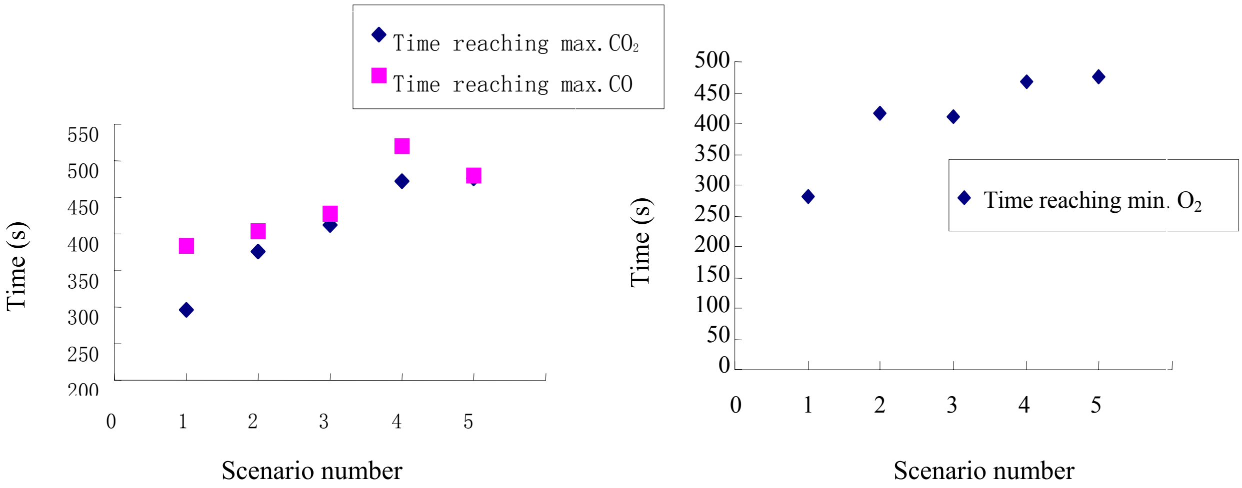


Fig. 8: Time to reach the maximum and minimum concentration of gases under different scenarios

11. CONCLUSION AND DISCUSSIONS

- Operating the mechanical smoke extraction system can effectively lower the smoke temperature and dilute the smoke concentration in the fire room.

- Using the specified value of 0.5 m for the smoke screen, all experiments indicated that smoke passed through the lower edge of the wall rapidly and spread to the adjacent zones. In other words, it was not very effective in blocking the smoke spreading. According to surveys, many shopping malls have adopted 0.5 m smoke screens. Since a fire develops generally rapidly in a shopping mall and the experiments have demonstrated that this value of 0.5 m is not effective in preventing smoke spread to adjacent zones, people would have difficulties in escape. However, adopting the fixed vertical wall for smoke blocking would affect the normal operation of the shopping mall if the wall is extended too low. In recent years, automatic smoke blocking walls have been developed, the walls can be further extended when a fire occurs. It is recommended to be widely used in shopping malls in China.

- The design smoke extraction rate of 60 $m^3m^{-2}h^{-1}$ as specified in the Chinese Fire Code [9] was used for all the experiments with mechanical smoke extraction in this study. It is found that smoke can be confined within the zone of fire origin for a relatively long time through controlling the extension of the vertical walls. The assumptions made in this study are: the fire is under control, flame spreading is not rapid, and the fire area is not expanding rapidly. Shopping malls are usually installed with sprinkler system which can control the fire at the early stage within a certain area, this situation is similar to the assumptions made.

- As observed from the scenarios with mechanical smoke extraction and make-up air, since hot smoke has stronger buoyancy, the air displaced from under the curtain would not disturb the smoke layer in the fire room. An upper smoke layer and a lower air layer can still be easily identified in the fire room, which helps in evacuation. The airflow from under the open curtain with a certain velocity also has an effect on preventing the outflow of smoke.

- For the three scenarios with mechanical smoke extraction and make-up air, smoke can be confined within the fire room under two scenarios (curtain edge at 1.2 m and 1.6 m above the floor). Under one scenario (curtain edge at 2 m above the floor), smoke flowed out of the fire room. When a balance is reached between the volume of smoke extracted and that produced from the fire source, the smoke layer interface will be kept stable at a certain height. If that height is higher than the lower curtain edge, smoke can be confined within the zone of fire origin.

- As observed from the vertical distribution of temperature and concentration of toxic gases in the experiments, two obvious layers of smoke and air can be kept inside the fire zone no matter there is mechanical smoke extraction or make-up air. The difference in temperature and concentration of gases within the smoke layer is comparatively smaller than the difference between the smoke layer and the air layer. It indicates that in a space with an area of hundreds of square metres and with a low ceiling, it is reasonable to use the two-layer zone model for simulating the smoke movement.

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