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SIMULATION OF AN ATRIUM FIRE USING CCFM.VENTS

by

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SUMMARY

A fire occurred in a Karaoke restaurant adjacent to an atrium space of a three-story shopping mall in Hong Kong. Smoke spread to the atrium space rapidly and accumulated at the roof. It was suspected to be an arson fire since all the sprinkler heads were actuated but did not discharge water. The program CCFM.VENTS (Consolidated Compartment Fire Model application code named VENTS) developed at the National Institute of Standards and Technology is used to simulate the fire environment. Based on the simulated results, the thermal sensitivity of sprinkler heads at upper levels is studied. Further, the growth of the smoke layer with natural and forced ventilation is studied. It seems installing smoke extraction systems is important in atrium buildings.

INTRODUCTION

Many atria and covered shopping malls[1] have been built in Hong Kong[2, 3] since 1980. Perhaps, it is the city having the highest number of atrium buildings in the world. The design was started[4] while developing the eastern part of the Tsim Sha Tsui (known as the TST East). Now, atria can be found in large-scale development projects such as multi-level shopping centres, luxurious hotels, and prestigious office buildings. The design is so popular because comfortable environment is usually found at the atrium floors by incorporating luxury decoration, plants or even musical ponds.

Although so many atria were built, very few fires were reported in those buildings in Hong Kong. The worst case was a fire which occurred in a 3-story shopping mall having an atrium space in December 1990. The fire was suspected to be an arson fire started in a ground floor Karaoke restaurant during midnight. The sprinkler system was shut off, and no water was discharged upon actuation of the sprinkler heads. Because the atrium space is of open design, smoke spread rapidly to the adjacent areas and filled up the whole mall. The fire was extinguished by firefighters who arrived before flashover occurred. The accumulated smoke was extracted by breaking the glass roof. Black stains were found everywhere inside the building, and the estimated loss was HK$20 millions.

The objective of the present article is to investigate the fire environment of this case using the zone model, CCFM.VENTS (Consolidated Compartment Fire Model application code named VENTS) developed by Cooper and Forney[5-9] at the Building and Fire Research Laboratory, National Institute of Standards and Technology, U.S.A. From the results, some knowledge on a real atrium fire can be achieved. One more interesting point is that all the "normal" sprinkler heads at the upper levels were actuated except the "concealed" ones. Thermal response of sprinkler heads in this atrium is also evaluated. Lastly, the growth of the smoke layer at the atrium space with natural and forced ventilation systems is studied.

The following section (Zone Fire Model) describes the general physical principle behind zone models; the next section is on the application of CCFM.VENTS for simulating the fire environment in this particular atrium. Subsequent sections discuss the thermal response of sprinkler heads and smoke extraction from the atrium; the paper ends with a conclusion.

Fire Zone Model

Simulating a building fire is a very difficult problem since it would involve interaction of complex processes. The set of equations describing the heat and mass transfer is highly nonlinear and coupled. Many fire models[10] are available in the literature. Basically, there are two kinds of deterministic fire models. One approach is on solving the system of partial differential equations directly from the physics concerned. This is known as "field model" and its development is still at the preliminary stage[11-13]. Actually, people would label it as a computational fluid dynamics problem since combustion of solids has not yet been simulated realistically. Further research is needed both in modeling the problem as well as the numerical schemes concerned. The computing time of this approach is usually very long, and the model can be used for simulating a two-dimensional preflashover fire in big atria[13, 14].

Another approach is to put in some empirical data for simplifying the set of equations. This is known as "zone model" and many models[15-17] have been reported in the past decade. There, a fire plume above the burning object acts as a source for transferring heat and mass. It would entrain air and other gases as it rises and then forms a ceiling jet at the ceiling. It is then deflected sideways, and a stratified smoke layer is formed when it is blocked by a vertical wall. Therefore, the enclosure can be divided into three regions: the upper hot smoke layer, the lower cool air, and the fire plume. All these regions are considered to be in gaseous phase. The control volume concept is used to derive the mathematical equations. Physically, the control volume is chosen from the observation in an enclosure fire. Since the fire plume volume is negligible compared to that of the upper hot smoke layer and the lower cool air, it can be considered as part of the upper control volume. Different workers had put in different expressions in their zone models. The set of conservation equations used in different models has been described extensively in many articles[15-17].

The fire environment in the paper is simulated using the zone model CCFM.VENTS (Consolidated Compartment Fire Model application code named VENTS) developed at the National Institute of Students and Technology, U.S.A.[5-9]. CCFM.VENTS is a multi-room fire model which simulates the fire environment (e.g., smoke layer-interface elevation, temperatures, and concentrations of products of combustion) in each room using the two layer zone concept. Both forced and natural ventilation in vents between rooms can be simulated. Also wind effects, stack effect, and room environments of arbitrarily high pressure can be studied. Application to simulate fire in a room with a horizontal hole has been reported by Cooper and Forney[6]. The sets of equations are derived from the conservation laws of mass, energy and chemical species described elsewhere[5-9] and will not be repeated here.

Fire Simulation

A fire occurred at the ground floor of a Karaoke restaurant adjacent to the 3-story atrium space in a shopping mall in Hong Kong. The atrium is of size 12 m x 12 m and height 11 m above the floor level. Not much scientific information was obtained in the investigation after the fire. But from the observations and interviews with the occupants, some rough idea was obtained. This fire was suspected to be an arson fire, and the sprinkler pump was found to be turned off purposely. Smoke spread rapidly from the fire compartment, filled up the atrium and then spread to the upper levels before firefighters arrived. Many sprinkler heads at the corridor of the upper levels were actuated but no water discharged. The shops located at the first level were not affected as there was no evidence of smoke spreading to those areas. The layout of the part of interest for the atrium is shown in Figure 1 together with the fire compartment indicated. The floor area at the atrium and the Karaoke restaurant are taken to be 144 m^2 and the initial temperature being 22°C.

Now, the fire environment is simulated using the program CCFM.VENTS. The part of interest

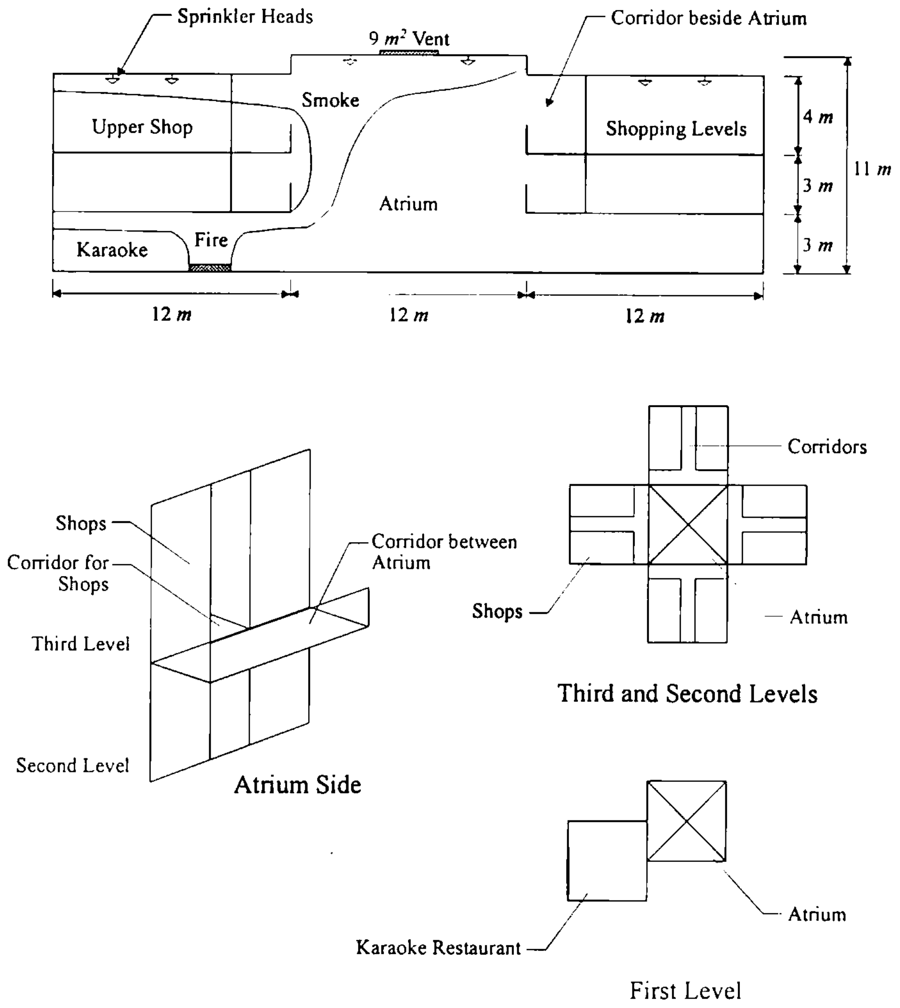

Figure 1. Atrium space concerned.

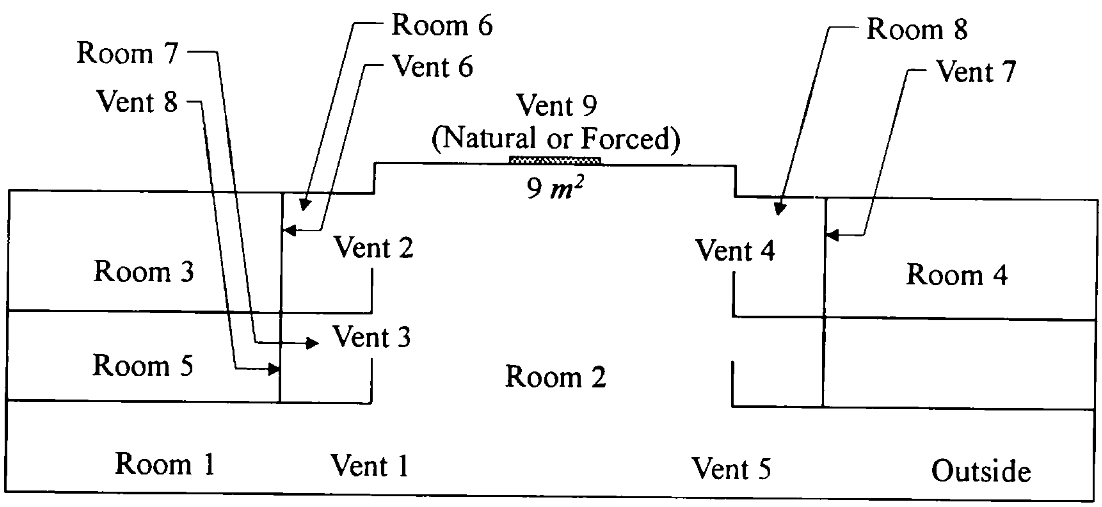

Figure 2. Configuration for fire simulation.

in the mall is composed of eight rooms numbered as shown in Figure 2, and summarised in Table 1. The corridor surrounding the atrium at one side is taken to be a room with two vents, one to the atrium and the other to the corridor of the shopping malls. Shops are partitioned by glass walls, and the doors are assumed to be closed when there is a fire. Therefore, only the corridors at the upper levels are simulated. Because there is a room number limitation in the zone model, floor area of the corridors at the third level are set to be twice of the individual size, and the floor area of the corridors at the second level being four times the actual value. Room 1 is the fire compartment, room 2 is the atrium, rooms 3 and 4 are the corridors for the shops at the third level, rooms 6 and 8 are the corridors beside the atrium at the third level, room 5 is the corridor for the shops at the second level and room 7 is its corridor beside the atrium. All the vents are numbered in Figure 2 and Table 2 with vent number 5 opened to the outside atmosphere. The vent number 9 at the top of atrium, (i.e., room 2 in Figure 2) is assigned for studying the effect of smoke ventilation.

A 5 MW fire is assumed to start at the Karaoke restaurant. The atrium is of open design where the other shopping levels are not separated. Therefore, smoke was reported to spread to those places within a short time. From the simulation, it is ob-

Table 1: Summary of rooms and vents.

Rooms:

Room Number	Floor Area/m^2	Floor Height/m	Ceiling Height/m
1	144	0	3
2	144	0	3
3	36 (x2)	6	4
4	36 (x2)	6	4
5	36 (x4)	3	3
6	36 (x2)	6	4
7	36 (x4)	3	3
8	36 (x2)	6	4

Vents:

Vent Number	Config-uration	From Room No.	To Room No.	VentBottom Area/m^2	Height w.r.t. floor of 'from number'/m	Top Height/m
1	V	1	2	18	0	3
2	V	2	6	24 (x2)	8	10
3	V	2	7	24 (x4)	4.5	6
4	V	2	8	24 (x2)	8	10
5	V	2	Outside	36 (x3)	0	3
6	V	6	3	12 (x2)	0	4
7	V	8	4	12 (x2)	0	4
8	V	7	5	9 (x4)	0	3
9 (Natural or forced vent)	H	2	Outside	9 (x1)	11	11
	V: Vertical H: Horizontal					

served that the smoke temperature and smoke layer thickness of the fire compartment and the other rooms increased rapidly. Transient height of elevation for the smoke layer in the atrium and its smoke temperature are shown in Figures 3 and 4 respectively. The smoke temperature at the corridors to upper shop (rooms 3 and 4) is shown in Figure 5. A summary of the smoke spreading pattern 2000 sec after the fire is presented in Figure 6. The smoke layer thickness at the atrium space is about 8.17 m (i.e., 74.3% of the ceiling height). Because the atrium is rather small, having volume only of 1584 m^3, the smoke temperature is about 137°C. This is hot enough to actuate the normal 68°C rated sprinkler heads at the atrium roof. But the actuation time depends on the thermal sensitivity of the sprinkler heads governed by the time constant or the Response Time Index (RTI). It might be quite long depending on other conditions[18].

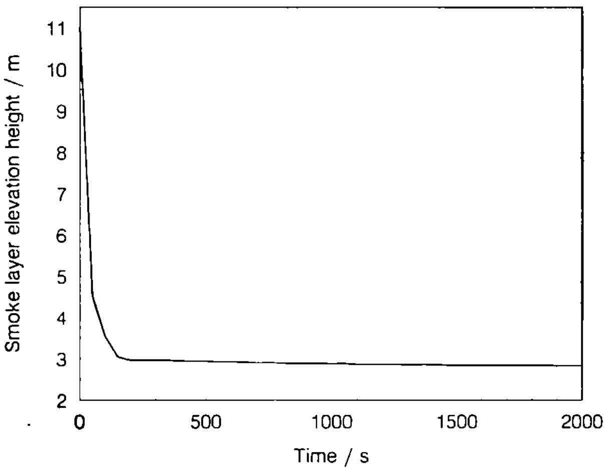

Figure 3. Smoke layer elevation height at the atrium.

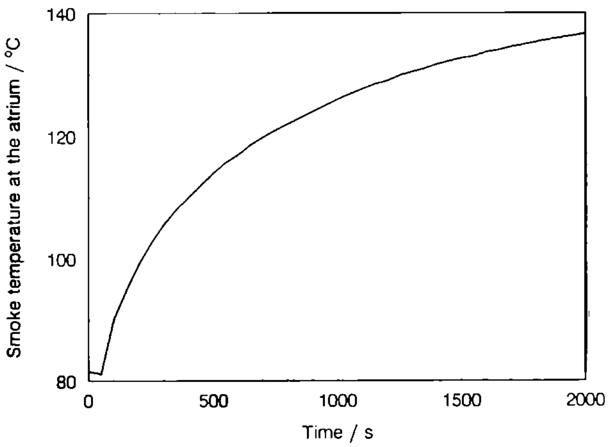

Figure 4. Smoke temperature at the atrium.

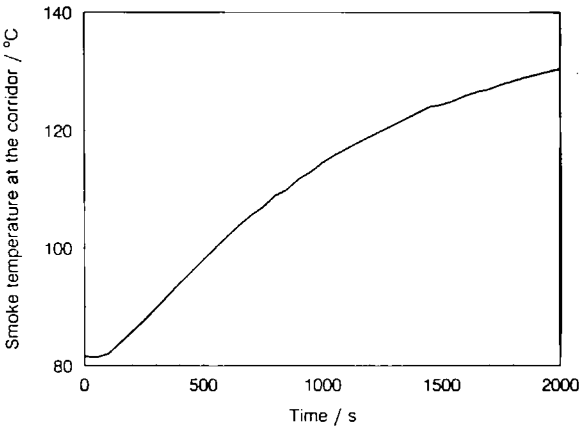

Figure 5. Smoke temperature at the upper corridor for shops (rooms 3 and 4).

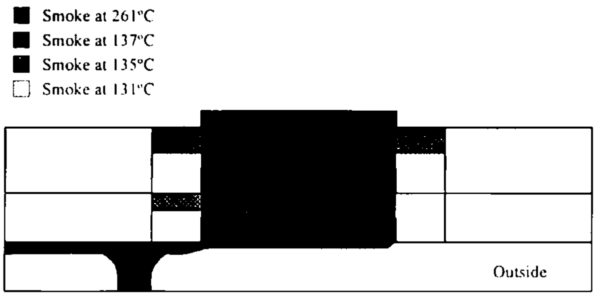

Figure 6. Predicted smoke pattern.

At the corridor of the upper shops, i.e., rooms 3 and 5, the compartment is full of smoke with temperature 131°C. This can actuate all the normal sprinkler heads of 68°C temperature rating at the upper levels if the fire is of thermal power 5 MW.

The fire environment can be predicted easily using the model CCFM.VENTS. Now, the thermal power of the fire at the Karaoke restaurant is changed. Simulations are repeated by taking values of 4 MW, 3 MW, 2 MW and 1 MW respectively. There is not much difference on the predicted smoke layer thickness at the atrium in time 2000 sec after starting the fire, but the smoke temperatures change to 119°C, 101°C, 84°C and 66°C respectively. The upper shops are also full of smoke but the predicted temperatures are 114°C, 97°C, 82°C and 66°C respectively. Anyway, the simulated fire environments agreed with the observation reported by the occupants and firefighters who were presented in that fire. Smoke spread out rapidly from the Karaoke restaurant, filled up almost the whole atrium space, and then spread to the corridors at upper levels. The sprinkler heads were actuated. A fire of thermal power 5 MW would be able to give such results.

Thermal Responses of Sprinkler Heads

It is observed that all the normal 68°C rated sprinkler heads at the upper level were actuated. The predicted results on the smoke temperature can be used to justify the situation. The time required to heat the sprinkler head up to the actuation temperature can be predicted, but this is possible only when the smoke temperature is higher than the temperature rating of the sprinkler heads. For this simulation, a 5 MW fire at the Karaoke restaurant would give a smoke temperature of 137°C. This should be hot enough to operate a 68°C rated sprinkler head. The heat transfer between the fire environment and the thermal sensing element of the sprinkler head is described by the following thermal response equation:

$$\frac{d(\Delta T_L)}{dt} = \frac{\Delta T_g - \Delta T_L}{\tau} \qquad 1$$

where ΔT_L and ΔT_g are the excess temperatures of the sprinkler head and smoke respectively, τ is the time constant of the sprinkler head which is related to the mass, specific heat, surface area and average convective heat transfer (depends on hot air speed) of the thermal sensing element.

The actuation time t_a required to heat up an ordinary liquid-filled bulb sprinkler head of time constant 288 sec under a constant hot air stream at temperature ΔT_g such as in the plunge test[19] to an excess temperature of 46°C can be calculated:

$$t_a = 288 \ln \left(\frac{\Delta T_g}{\Delta T_g - 46} \right) \qquad 2$$

The actuation time would be 158 sec for a 5 MW fire in the Karaoke restaurant. This will be extended to 200 sec for 4 MW, 268 sec for 3 MW and 390 sec for 2 MW fires respectively. A 1 MW fire at the Karaoke restaurant will not give a smoke temperature hot enough to actuate the sprinkler heads at the corridor in the third level. Normal sprinkler heads can be actuated if the thermal power of the fire is greater than 2 MW. But from the interviews with the occupants, those sprinkler heads were actuated within the short time of about 3 minutes after discovering the fire. Therefore, thermal power of the fire would be very close to 5 MW. However, the concealed type of sprinkler heads were found not to actuate. The thermal Response Time Index might be too large and give a slower response.Beyler, Craig

Smoke Extraction System

Both natural and ventilation systems can be simulated by the program CCFM.VENTS. Now, the effect on the growth of smoke layer inside the atrium due to smoke extraction system is studied. For a 5 MW fire at the Karaoke restaurant, the predicted smoke layer thickness at the atrium 2000 sec after starting the fire is 8.17 m and the smoke temperature is 137°C. A natural horizontal vent of area 9 m^2 is assumed to open at centre of the top of the atrium (i.e., numbered as vent 9 in room 2 of Figure 1) as soon as there is a fire. The transient elevation heights of the smoke layer is plotted in Figure 7. The natural vent is not very effective in extracting smoke as the predicted smoke layer thickness and temperature at the atrium are also 8.17 m and 137°C in time 2000 sec after starting the fire. Now, forced ventilation is considered, and it would be operated when the fire is started. The fan is installed at that horizontal vent 9 in the top of the atrium (i.e., room 2 in Figure 1).

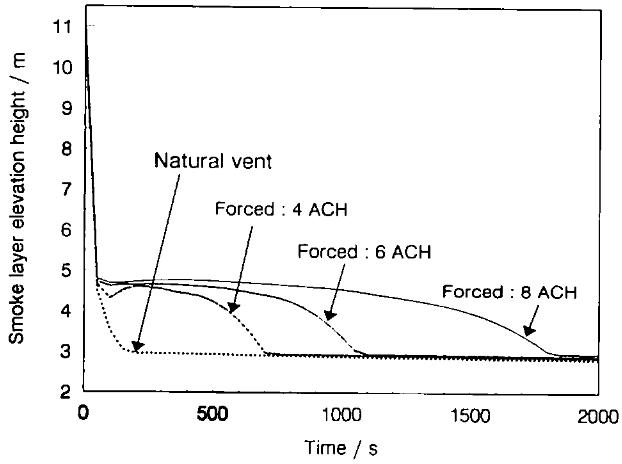

Figure 7. Effect of ventilation on the smoke layer elevation height at the atrium.

Extraction rates of 4, 6 and 8 air changes/hour are simulated with the results on the elevation height of the smoke layer plotted also in Figure 7. There is a reduction of the steady-state smoke layer thickness. In 2000 sec after starting the fire, the smoke layer thickness are 8.12 m, 8.08 m and 8.03 m; and the smoke temperatures at the atrium are predicted to be 130°C, 125°C and 118°C, respectively, for extraction rates of 4, 6 and 8 air changes/hour.

However, the rate of smoke layer development decreased, and for an extraction rate of 4 air changes/hour, 700 sec were required to fill smoke up a steady-state thickness, in comparison to about 180 sec for natural ventilation. The time required to fill smoke up to the steady-state thickness would be

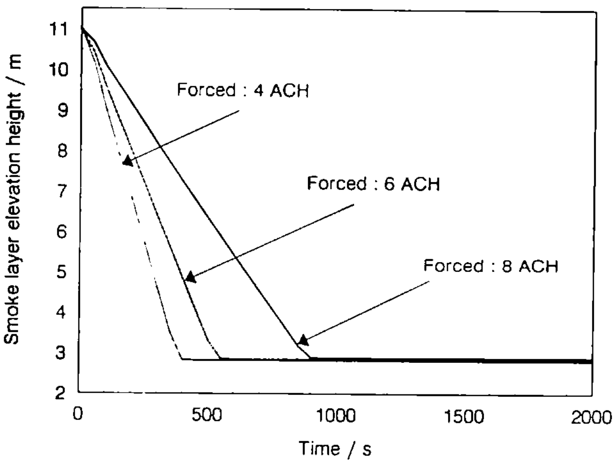

Figure 8. Effect of forced ventilation on the smoke layer elevation height at the atrium without upper levels.

delayed to about 1100 sec for extraction rates of 6 air changes/hour and 1700 sec for extraction rates of 8 air changes/hour. Note that for the extraction rate of 4 air changes/hour, the smoke layer thickness decreased at time after 100 sec, but increased again starting at about 200 sec onwards. This is because the atrium itself is of open design, and the smoke layer thickness would not just decrease as in the case of a closed atrium where the smoke filling process is just like an inversion of water filling a basin. To illustrate this fact, the upper layers are disconnected from the atrium, *i.e.*, vents 2, 3, and 4 are all closed. Simulation of extraction rates of 4, 6, and 8 air changes/hour with a 5 MW fire are performed, and the transient smoke elevation heights are plotted in Figure 8. It is observed that smooth curves without "dips" as in Figure 7 result. The smoke temperature would be slightly reduced if the smoke extraction rates increased. Forced ventilation systems have the advantage of reducing the smoke layer thickness, and installing a smoke extraction system in an atrium seems to be important.

Conclusions

Fire safety science and technology have advanced to the point where zone-type computer fire models can be effective and practical tools for investigating and explaining real fire phenomena (see, e.g., the analysis by Nelson[20] of the First Interstate Bank Building fire). Such models can be very useful, even when detailed scientific information on a particular fire of interest is not available.

In the present paper, a fire in a Karaoke restaurant which opens onto a 3-story atrium was simulated using the multi-room zone fire model CCFM.VENTS. The model was used to predict the fire environment, particularly the transient elevation of the various smoke layers and their temperatures. Also, model simulations were used to evaluate the performance of fire protection systems. This included the thermal responses of sprinkler links and impact on smoke-layer growth of different possible smoke ventilation/extraction systems.

The CCFM.VENTS simulations confirmed the phenomenon of smoke filling as reported by the atrium building occupants. Smoke was found to lead to severe problems in this open atrium facility. The model was used to estimate the thermal power of the fire in the Karaoke restaurant, which was found to be about 5 MW. This was the fire strength that led to predicted upper-level sprinkler head actuations similar to those reported during the actual fire event. Finally, the analysis indicated that an installed smoke extraction system would have been effective in controlling the smoke, and that this would likely be true for fires in atria similar to the one studied here.

Acknowledgment

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