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# SCALE MODELLING STUDIES ON ATRIUM SMOKE MOVEMENT AND THE SMOKE FILLING PROCESS

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## SUMMARY

The smoke filling process in a scale model of an atrium building with natural vents was studied. The model was a 1/25 scale model of a three-level shopping mall. An optical visualization technique was applied to observe the smoke movement pattern and the smoke filling process in the atrium space. Transient variation of air speed, temperature, and smoke layer thickness were studied by correlating the time scale on the model with the real situation through the preservation of the Froude number. A comparison with the empirical relationships was made. The zone model CCFM.VENTS developed at the Building and Fire Research Laboratory, National Institute of Standards and Technology, USA, was used to verify the results.

## INTRODUCTION

Atrium buildings[1], although not a very new feature elsewhere, are now popular in Hong Kong[2]. Out of the many technical problems encountered as a result of the large volume in an atrium space, firesafety is the most important issue to be considered. Very little research work has been reported on atrium fires, and very few design guides with strong scientific background have appeared in the construction industry literature[3-6]. Research works reported in the literature include the full-scale atrium experiments on smoke extraction[7], scaled models for studying smoke movement and smoke control[8], semi-empirical studies[9-12], and finally, the numerical simulations of the fire environment using both zone and field modelling techniques[2,13-14]. Results from those studies are not satisfactory for formulating workable regulations and codes for designing safe atrium buildings[3-6]. Consequently, further investigational works are urgently required. "Smoke" is identified to be a key factor, and "smoke control" must be dealt with carefully. The smoke control system is usually integrated with other fire services systems such as sprinkler, fire detection, fire hydrant and hose reel systems. Before providing any "realistic" design data to answer questions such as how much smoke will be emitted and what the design fire size will be, smoke movement in the atrium spaces must be known. Studies with full size atrium buildings would give the actual picture of fire performance and the smoke filling process. However, this is very expensive, and the high cost would limit the number of tests that would be performed. An alternate method would be to simulate the smoke spreading pattern with scaled models under controlled conditions. With data on the transient development of the smoke layer thickness, more design parameters could be worked out.

Experimental studies with scale models would require the preservation of many parameters. Scaling laws[15-18] have been developed and are in fact available in literature for studying preflashover fires. At the early stage of a fire, heat is mainly transferred by convection from the burning object to upper ceiling. Buoyancy is the driving force for smoke movement in a naturally ventilated building. Accordingly, so long as the necessary parameters are preserved, scaling down the model will yield good results. The purpose of this paper is to report on a study applying this technique to investigate the smoke filling process in a scaled model of an atrium building with natural vents. From the observed results, it is possible to assess the effectiveness of natural vents in controlling smoke.

## Scaling Effects

With the assumptions that smoke in the atrium is a homogeneous gas at a uniform temperature, the outside ambient air temperature is constant, the effect of viscosity and the species transfer is negligible, and the gas is incompressible, and by applying the Bousinessque approximation, the set of equations of motion (in tensor notation for simplicity, with $x_1$, $x_2$ and $x_3$ corresponding to x, y and z in a Cartesian co-ordinate system) for the smoke movement may be given by[8,18]:

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial \bar{u}_i}{\partial t} + \bar{u}_j \frac{\partial \bar{u}_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \bar{P}}{\partial x_i} + g_i \beta(\bar{\theta} - \theta_0) + v_t \frac{\partial^2 \bar{u}_i}{\partial x_j \partial x_j} \tag{2}$$

$$\rho c_p \left( \frac{\partial \bar{\theta}}{\partial t} + \bar{u}_i \frac{\partial \bar{\theta}}{\partial_{xi}} \right) = \rho c_p \alpha_t \frac{\partial^2 \bar{\theta}}{\partial x_i \partial x_i} + Q \tag{3}$$

where $\bar{u}$ is the mean velocity, t is the time, ρ is the density, P is the pressure, $\theta$ is the temperature, $c_P$ is the specific heat and Q is the heat release rate.

This set of equations can be converted into dimensionless form by introducing four numbers $\Pi_1$, $\Pi_2$, $\Pi_3$ and $\Pi_4$ (corresponding to the length $L_o$, velocity $u_o$, change in pressure $\Delta P_o$ and temperature $\theta_o$) defined as:

$$\Pi_1 = \frac{L_o}{u_o t_o} \tag{4}$$

$$\Pi_2 = -\frac{1}{\rho}\frac{\Delta P_o}{u_o^2} \tag{5}$$

$$\Pi_3 = g_i \beta \Delta\theta_o \frac{L_o}{u_o^2} \tag{6}$$

$$\Pi_4 = \frac{Q_o}{\rho c_p u_o \theta_o L_o^2} \tag{7}$$

The following scaling laws are derived with the subscripts M and R to denote the model and real building respectively:

$$\frac{Q_M}{Q_R} = \left(\frac{\Delta\theta_M}{\Delta\theta_R}\right)^{3/2} \left(\frac{L_M}{L_R}\right)^{5/2} \tag{8}$$

$$\frac{t_M}{t_R} = \left(\frac{\Delta\theta_M}{\Delta\theta_R}\right)^{-1/2} \left(\frac{L_M}{L_R}\right)^{1/2} \tag{9}$$

$$\frac{u_M}{u_R} = \left(\frac{\Delta\theta_M}{\Delta\theta_R}\right)^{1/2} \left(\frac{L_M}{L_R}\right)^{1/2} \tag{10}$$

$$\frac{\Delta P_M}{\Delta P_R} = \left(\frac{\Delta\theta_M}{\Delta\theta_R}\right) \left(\frac{L_M}{L_R}\right) \tag{11}$$

The combustion products might recirculate to the burning zone and affect the yield of combustion products in the real case. It is essential that temperature and gas concentrations are reproducible from scale to scale, *i.e.*, $\Delta\theta_o$ = constant[8, 18]. The following relationships among Q, t, L and u can be derived using the four Π numbers.

$$\frac{Q_M}{Q_R} = \left(\frac{L_M}{L_R}\right)^{5/2} \tag{12}$$

$$\frac{t_M}{t_R} = \left(\frac{L_M}{L_R}\right)^{1/2} \tag{13}$$

$$\frac{u_M}{u_R} = \left(\frac{L_M}{L_R}\right)^{1/2} \tag{14}$$

The technique of Froude modelling can be used for a large scale fire because the air flows are generated by convection due to buoyancy. Viscous effects are less important for fully developed turbulent flows except near the boundaries. Therefore, the Froude number Fr[8] is very useful and may be given by:

$$Fr = \frac{\text{Buoyancy Force}}{\text{Inertia Force}} \qquad (15)$$

This number can be preserved by maintaining $u \sim l^{1/2}$. However, the heat output of fire Q might be important and the scaling law assumes that it is related to $l^{2/5}$ [15].

## Scale Model

A 1/25th scale model of a linear atrium in a shopping mall was constructed to study the smoke filling process. The atrium is in a three-level shopping mall with a smoke reservoir at the ceiling. The details of the model setup are shown in Figure 1. The model was constructed of cork board and perspex panels with the junctions sealed with clay. The bottom of the fire compartment ceiling was protected by a layer of ceramic fiber blanket with a thickness of 1 mm. For this model, the time in the real atrium $t_R$ is related to the model time $t_M$ by Equation 13, which is:

$$t_R = 5\, t_M \qquad (16)$$

Vents of different area were cut in the roof, and the make-up air inlet was constructed at the lower level. Three ventilation conditions V1, V2, and V3 with the same total vent area of about 5.8 $m^2$ but with different distribution were studied. There was a vent of size 2.4 m x 2.4 m for ventilation design condition V1, two vents of size 1.7 m x 1.7 m for V2, and three vents of size 1.38 m x 1.38 m for V3. The separate distances of the vents are shown in Figure 2. The total venting area was designed in compliance with the general requirements of a smoke extraction system[19-21], *i.e.*, to have a minimum rate of eight air changes per hour; maximum inlet and outlet velocities of 3 $ms^{-1}$ and 6 $ms^{-1}$ respectively; and a minimum air supply flow rate equal to 80 percent of the extraction rate.

A 1.6 kW methanol fire corresponding to a 5 MW fire size in the real site according to Equation 12 was used in the model. The flow rate of methanol was controlled by a tap and a rotameter. Because burning methanol would give a clean fire, gun powder was used to generate smoke. Chromel-alumel thermocouples placed at 40 mm intervals were used to measure the temperature distribution.

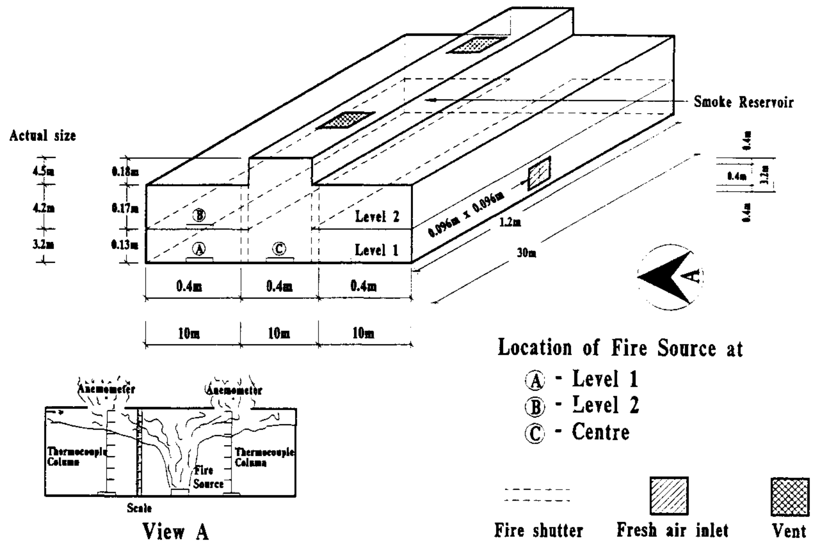


Figure 1. Model of the Atrium.

The velocity distribution of the incoming air and exhaust air was measured by hot-wire anemometers put at the open end of the lower level and the top of the roof respectively. The mass flow rate of smoke ($M_e$) through the vents can be obtained by measuring the ventilation area and the temperature.

The transient development of smoke layer was measured by a meter stick. The optical arrangement shown in Figure 3 was provided to give a clear view of the smoke movement patterns. This would give an illuminated sheet so that photographs of the smoke layer at a certain plane can be taken.

## Experimental Studies

The transient development of the smoke layer for fire at different locations under the three ventilation conditions V1, V2, V3 as shown in Figure 2 was studied. There were a total of 10 tests, and a summary of the experimental results is shown in Table 1. In each case, transient values of the temperature, velocity and smoke layer thickness were determined. A typical photograph of the smoke filling process for test 1-1 is shown in Figure 4. The transient variation of the smoke layer thickness in the atrium space for each test under the three venting conditions V1, V2 and V3 with the fire located at level 1, 2 and the

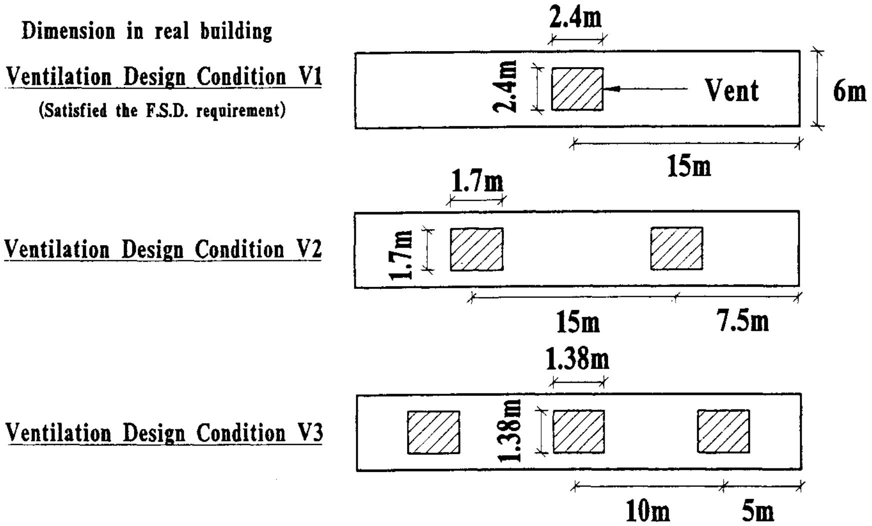


Figure 2. Plan of the Roof Showing the Three Ventilation Conditions.

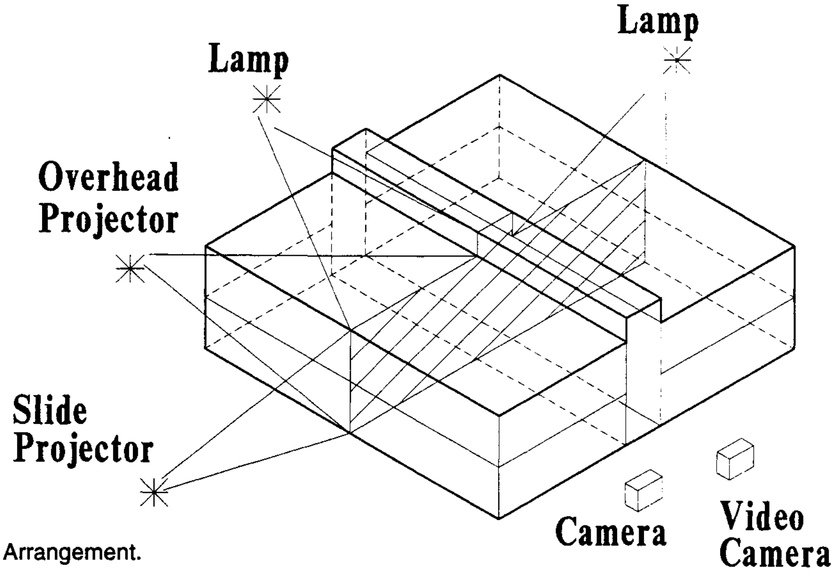


Figure 3. Optical Arrangement.

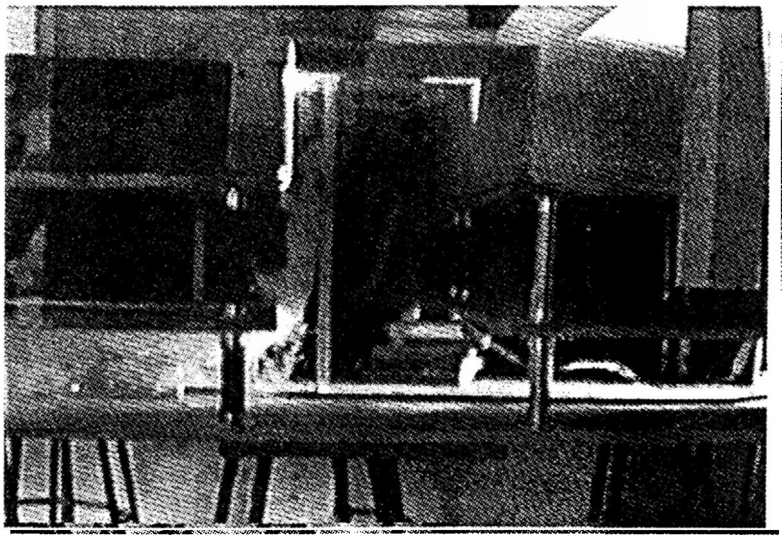

Figure 4. Typical Photograph of the Smoke Filling Process.

center of the atrium are shown from Figures 5, 6 and 7 respectively. Note that the model time is transformed to the real time through Equation 16. For the fire located at level 1, it can be seen from Figure 5 that the ventilation V3, although with the same venting area as the other configurations, would give the slowest rate of smoke filling in the atrium space. In fact, the smoke layer thickness went up only to 25 percent of the ceiling height. There were not many differences between venting conditions V1 and V2, yielding a smoke layer thickness of 35 percent of the ceiling height.

For the fire located at level 2, in view of the results shown in Figure 6, again the ventilation condition V3 provided the slowest rate of smoke filling on the atrium. The smoke layer thickness for this case went up to 15 percent only, which was much lower than the 35 percent for ventilation condition V1 and V2. The fire at level 2 gave a thinner smoke layer than for ventilation condition V3. For the fire at the atrium center, the smoke layer thickness for all the three ventilation conditions went up to 35 percent. The times required for the smoke layer thickness to develop up to the maximum value were much shorter than for the other fire locations.

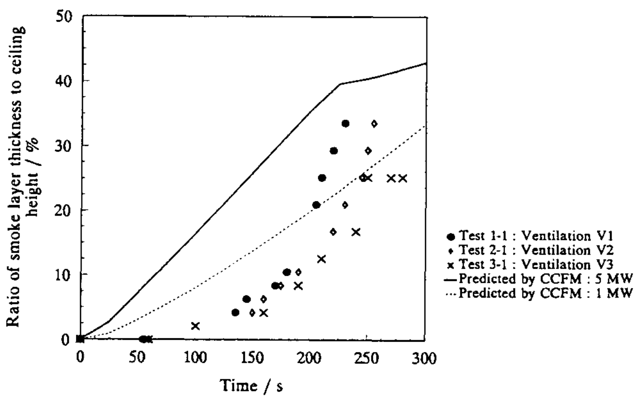


Figure 5. Development of the Smoke Layer in the Atrium Space for a Fire at the Shopping Mall Level 1.

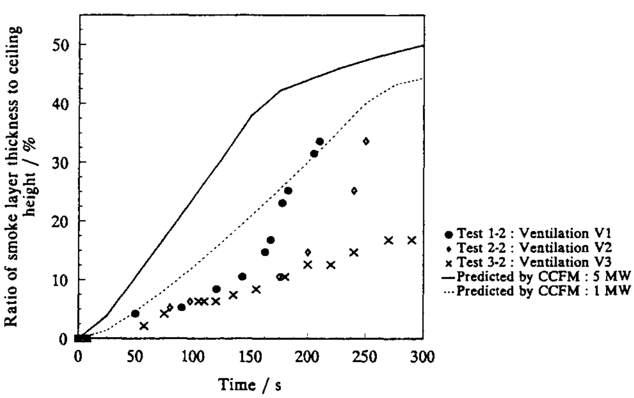


Figure 6. Development of the Smoke Layer in the Atrium Space for a Fire at the Shopping Mall Level 2.

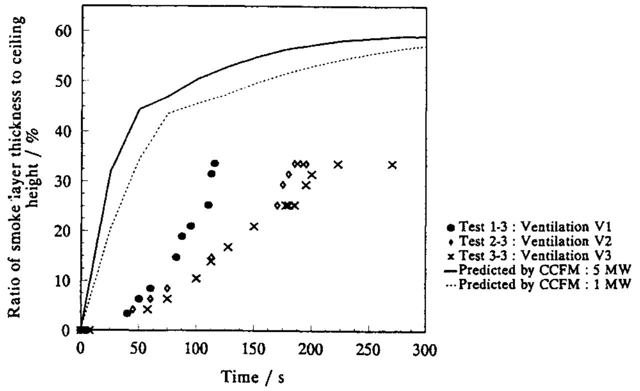


Figure 7. Development of the Smoke Layer in the Atrium Space for a Fire at the Centre of the Atrium Space.

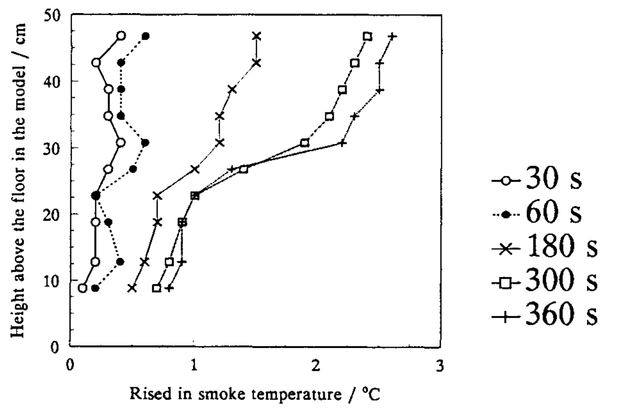


Figure 8. Vertical Distribution of Smoke Layer Temperature Rised in the Atrium for Test 1-1.

## Mass Flow Rate through the Vents

The purpose of the smoke reservoir in this atrium is to limit the spreading of smoke. However, horizontal air that moved to the screen would be blocked and then moved vertically downward. Air recirculation was found and smoke would be brought to the lower level. This was clearly illustrated when the fire was located at the centre of the atrium. Therefore, it is recommended that natural vents are installed to extract smoke from the reservoir. By comparing the results of different tests listed in Table 1, the most effective way of designing natural venting can be isolated.

The vertical temperature rise $\Delta\theta$ distribution along the center line of vent for Test 1-1 is shown in Figure 8. The maximum $\Delta\theta$ of the smoke layer for fire at different locations is shown in Figure 9. These values are roughly the same for the three different ventilation conditions as this value is dependent on the fire size. With the use of $\Delta\theta$ and venting area, the predicted mass flow rate through the vent $M_t$ can be estimated by the following Equation[9]:

**Table 1: Summary of Tests**

| Test number | Venting condition | Location of fire source |
|---|---|---|
| 1-1<br>1-2<br>1-3 | V1 | Level 1<br>Level 2<br>Centre |
| 2-1<br>2-2<br>2-3 | V2 | Level 1<br>Level 2<br>Centre |
| 3-1<br>3-2<br>3-3 | V3 | Level 1<br>Level 2<br>Centre |
| 4-1 | V3 with fire shutter | Level 1 |

**Table 2: Results on Mass Flow Rate through the Vents**

| Vent number | V1 (5.8 m²) | | V2 (2.9 m² x 2) | | |
|---|---|---|---|---|---|
| **Location of fire** | $M_e$ $kgs^{-1}$ | $M_t$ $kgs^{-1}$ | $M_e$ $kgs^{-1}$ | | $M_t$ $kgs^{-1}$ |
| | 1 | | 1 | 2 | |
| Level 1 | 5.4 | 7.4 | 3.1 | 3 | 3.7 |
| Level 2 | 6.3 | 7.4 | 4.3 | 4.1 | 3.6 |
| Centre | 6.6 | 7.3 | 4.3 | 5.2 | 3.7 |

$$M_t = C_v A_v \rho_e \left( 2g\Delta\theta \frac{d_s}{\theta_o} \right)^{1/2} \sim 0.1 A_v \rho_e (\Delta\theta)^{1/2} \tag{15}$$

where $d_s$ is the depth of smoke layer, $A_v$ is the area of vent, $C_v$ is the coefficient of vent and β is the thermal expansion coefficient.

A comparison between the measured mass flow rate $M_e$ and the predicted mass flow rate $M_t$ through the vent is shown in Table 2. Fairly good agreement between the predicted and measured results is obtained.

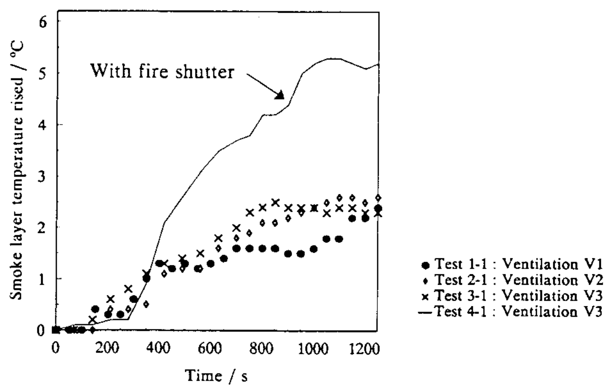


Figure 9. Smoke Layer Temperature Rised in the Atrium Space for a Fire at the Shopping Mall Level 1.

## Depth of the Smoke Layer

The time needed for the smoke to fill up the atrium can be correlated with the evacuation time. Figures 5 to 7 indicate that it took less than 3.5 minutes for the smoke to reach the bottom level of reservoir under ventilation condition V1 with a fire on level 1. The whole atrium would be filled up with smoke within 5 minutes. Similar situations occurred for the fire located at level 2 and at the center of the atrium for all Tests 1-1, 1-2 and 1-3. Hence, this venting design, although in compliance with the local regulation[19-21], would not be effective in controlling smoke.

If the number of vents was increased to two while the total venting area unchanged, the time taken for smoke development was delayed. As shown in Figures 6 and 7, a thinner smoke layer was formed when the fire source was located at level 2 and at the centre. Therefore, increasing the number of vents would decrease the interface height of the smoke layer and the mass flow rate.

For ventilation V3 shown in Figures 5 to 7, the smoke filling curves increased steeply first and then slowly over time. This indicated that the design with three vents separated 10 m apart would take smoke out at any location of fire source, leaving the void clear of smoke. The smoke layer can be maintained at the high level even 3 to 4 minutes following ignition of the fire. The curves showed that $\Delta\theta$ reached its maximum value when the source was located at the centre of atrium. It is seen in Figure 9 that the temperature at a lower region would be increased when the smoke layer was moving down to the floor level.

## Fire Shutter

Although the smoke can be kept at the high level for ventilation condition V3, it would spread into level 2 when the fire was located at level-1. Installing fire shutters seemed to be appropriate and necessary, and therefore Test 4-1 was performed to study the effect of fire shutters. Results on the smoke layer development at the atrium space are plotted in Figure 10. It is shown that the smoke layer moved down more rapidly than the case without fire shutters. However, smoke spreading to other levels was prevented.

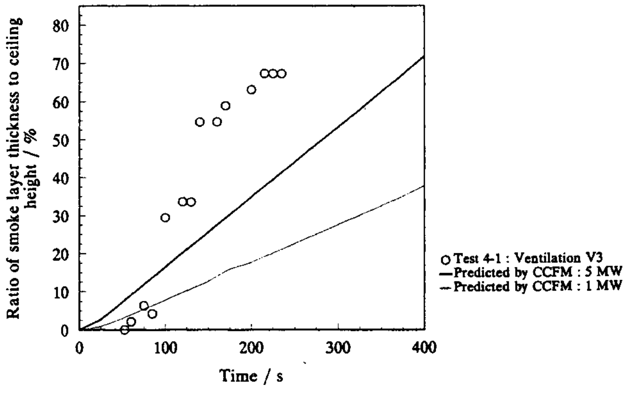


Figure 10. Development of the Smoke Layer in the Atrium Space for a Fire at the Shopping Mall Level 1 with Fire Shutter Operated.

## Simulation with the Zone Model CCFM.VENTS

The zone model CCFM.VENTS[22] was used to simulate the development of smoke layer in the full-size atrium space. A 5 MW fire satisfying the scaling law given by Equation 12 was used. Since the venting area for the three ventilation conditions V1, V2 and V3 was the same, the predicted results from this zone model were the same and results for fires at different locations are plotted in Figures 5 to 7 and Figure 10 as well. In the simulations, the predicted smoke layer developed much faster than was observed in the experimental data. However, when compared to the results of Test 4-1 with a fire shutter, a slower rate of smoke layer development was seen. A smaller fire of 1 MW is simulated and plotted in those figures. There was better agreement between the empirical and computational results for the smaller fire size. Perhaps, the correspondence of the heat in the model given by Equation 12 has to be modified or the actual heat transferred into the atrium space needs to be reduced by a factor denoting the percentage of convective heat transfer.

## Conclusion

With a 1/25 scale model of an atrium in a three-level shopping mall, both the qualitative picture of the smoke filling in the atrium space and the quantitative data on the smoke filling process for the full-size atrium were obtained. Results from the model were compared with the empirical expression[9] for determining the amount of smoke venting out, and also with the zone model CCFM.VENTS[22]. Fairly good agreements were found. Obviously, for smoke control, installing natural venting is the minimum design. However, with the same total vent area, several vents of a smaller area are better than a single larger vent. Lastly, the effects of fire shutters were demonstrated.

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