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A SYSTEMATIC EXPERIMENTS OF ROOM AND CORRIDOR SMOKE FILLING FOR USE IN CALIBRATION OF ZONE AND CFD FIRE MODELS FOR ENGINEERING FIRE SAFETY DESIGN OF BUILDINGS

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ABSTRACT

A series of full-scale experiments were carried out to investigate the smoke propagation behavior for t2-fires. The effect of corridor arrangement (size and smoke curtains) were analyzed. The corridor size and smoke curtains have beneficial effect to delay the smoke propagation to downstream corridors. In the experiments, quick mixing of smoke after the decay of fire was observed that result in blockage of corridors. In the prediction of smoke layer by using zone models, this effect is not taken into account. Thus there is a need to revise zone type equations to include smoke-air mixing during post decay period.

Keywords : full-scale experiment, smoke propagation, t^2-fire, zone model

1.INTRODUCTION

In the smoke control designs for evacuation safety, smoke layer height and temperatures are calculated for safety checking. Quite often, the design Heat Release Rate (HRR) is described by t^2-fires [1,2]

$$Q_f = \alpha t^2 \qquad (1)$$

where Q_f [kW] is design HRR, α [kW/s^2] is the fire growth rate, and t [sec.] is the time from ignition. Putting the design fires in the building to be designed, the smoke propagation is calculated typically by zone models [3-6] such as BRI2 and CFAST. To be certain with the calculated results, the models will have to be validated against design fire scenarios.

Both BRI2 and CFAST have been verified against many experimental data. However most of the experiments were carried out using steady HRR, mainly because of the simplicity of experimental procedures. Thus question may arise if those models are still valid for t^2-fires.

In this study, the series of full-scale experiments were carried out using t^2-fires. Fire room and corridor smoke filling process was measured. The size of the corridors and arrangement of smoke curtains were varied in several patterns. Using the measured data, comparisons were made between experimental results and the results by two zone models, BRI2 and CFAST.

2.EXPERIMENTAL PROCEDURE

2.1 Fire Source

Figure 1 shows the schematics of the fire source. A triangular shaped polyurethane mattress was used as a fire source. Base width is 600 [mm], while the height of the triangle is 900 [mm]. The thickness was 160 [mm]. Using three load cells, the mass loss rate was measured continuously. The Heat Release Rate was calculated by multiplying its heat of combustion 36 [kJ/g].

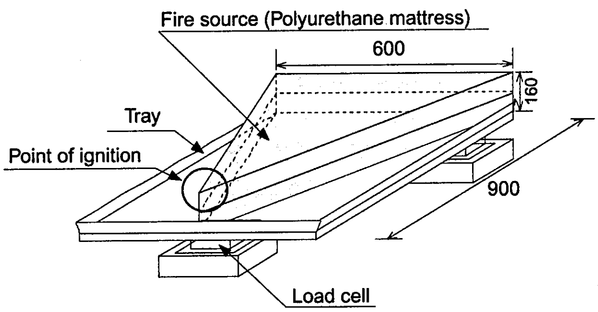

Figure 1 The schematic of the fire source (unit: mm)

To check the appropriateness of this method of HRR calculation, burn test was carried out using the Oxygen consumption calorimetry [7, 8]. Typical example for heat release rate curve is shown in Figure 2. HRR values measured by Oxygen consumption and by mass loss rate are in good agreement. After several tests, fire growth rate resulted in the range of 0.0058 to 0.0051[kW/s^2], while the duration of fire was about 3 minutes.

2.2 Room and Corridor Arrangement

The experiments were carried out on third floor of Full-Scale Fire Laboratory at the Building Research Institute. Figure 4 shows the arrangement of room and corridors. The dimension of the room of fire origin is W 7,900 x D3,300 x H 2,700 [mm]. Doorway size between fire room and corridor was W1,000 x H2,000 [mm]. Corridor ceiling height was 2,700 [mm].

In the fire room, wall surfaces and ceiling are covered by calcium silicate board. Corridor ceilings are covered by calcium silicate board. Corridor walls are covered by gypsum plaster board (thickness 12 [mm]). Table 1 summarizes the area of room and corridors.

The connection of the corridors was taken into consideration so that the experiment gives systematic results on the effect of corridor size and smoke curtains. The number of corridors was changed from 1 to 3. In some of the experimental patterns, the size (length) of corridors was changed. In summary we get 6 experimental patterns as shown in Table 2 and Figure 5.

Table 3 summarizes the opening condition of the doorways between corridor spaces. As shown in Figure 6, they were changed in tree ways. When the doorway is open, it has a smoke curtain at 2,000 [mm] above floor. When the doorway is almost closed, it has a small vent (up to 200 [mm] above floor) at the bottom.

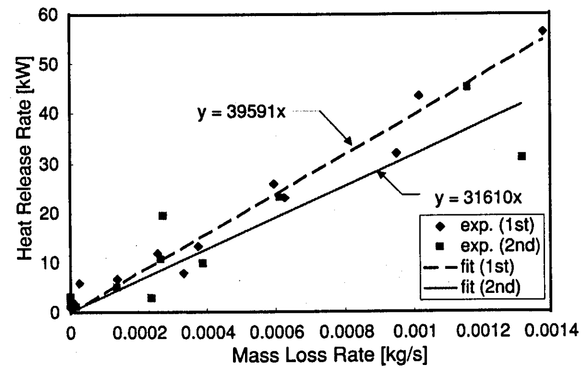

Figure 2 Correlation between HRR and mass loss rate

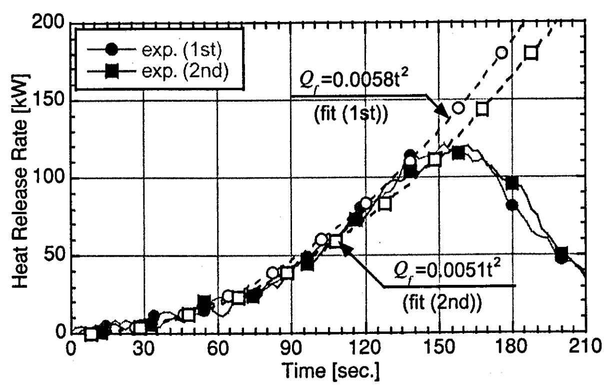

Figure 3 HRR of the fire source

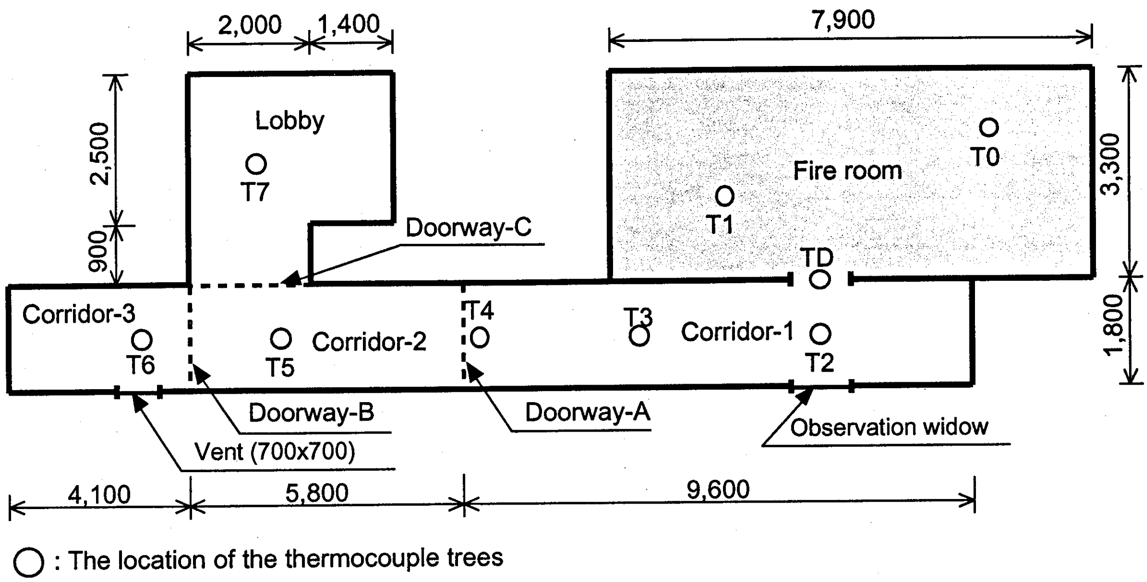

Figure 4 The arrangement of room and corridors, the location of thermocouple trees (unit: mm)

Table 1 The area of room and corridors

	Fire Room	Corridor-1	Corridor-2	Corridor-3	Lobby
Floor area [m^2]	26.07	17.28	10.44	7.38	10.30

Table 2 The condition of experimental patterns

Experimental pattern	Number of spaces	Condition of each space			
		1st	2nd	3rd	4th
A	2	Fire room	Corridor-1		
B	2	Fire room	Corridor-(1+2)		
C	2	Fire room	Corridor-(1+2+3)		
D	3	Fire room	Corridor-1	Corridor-2	
E	3	Fire room	Corridor-(1+2)	Lobby	
F	4	Fire room	Corridor-1	Corridor-2	Lobby

Table 3 The opening condition of the doorways

	Pattern A	Pattern B	Pattern C	Pattern D	Pattern E	Pattern F
Doorway-A	Bottom vent	Fully open	Fully open	Smoke curtain	Fully open	Smoke curtain
Doorway-B	-	Bottom vent	Fully open	Bottom vent	Bottom vent	Bottom vent
Doorway-C	-	-	Closed	Closed	Smoke curtain	Smoke curtain

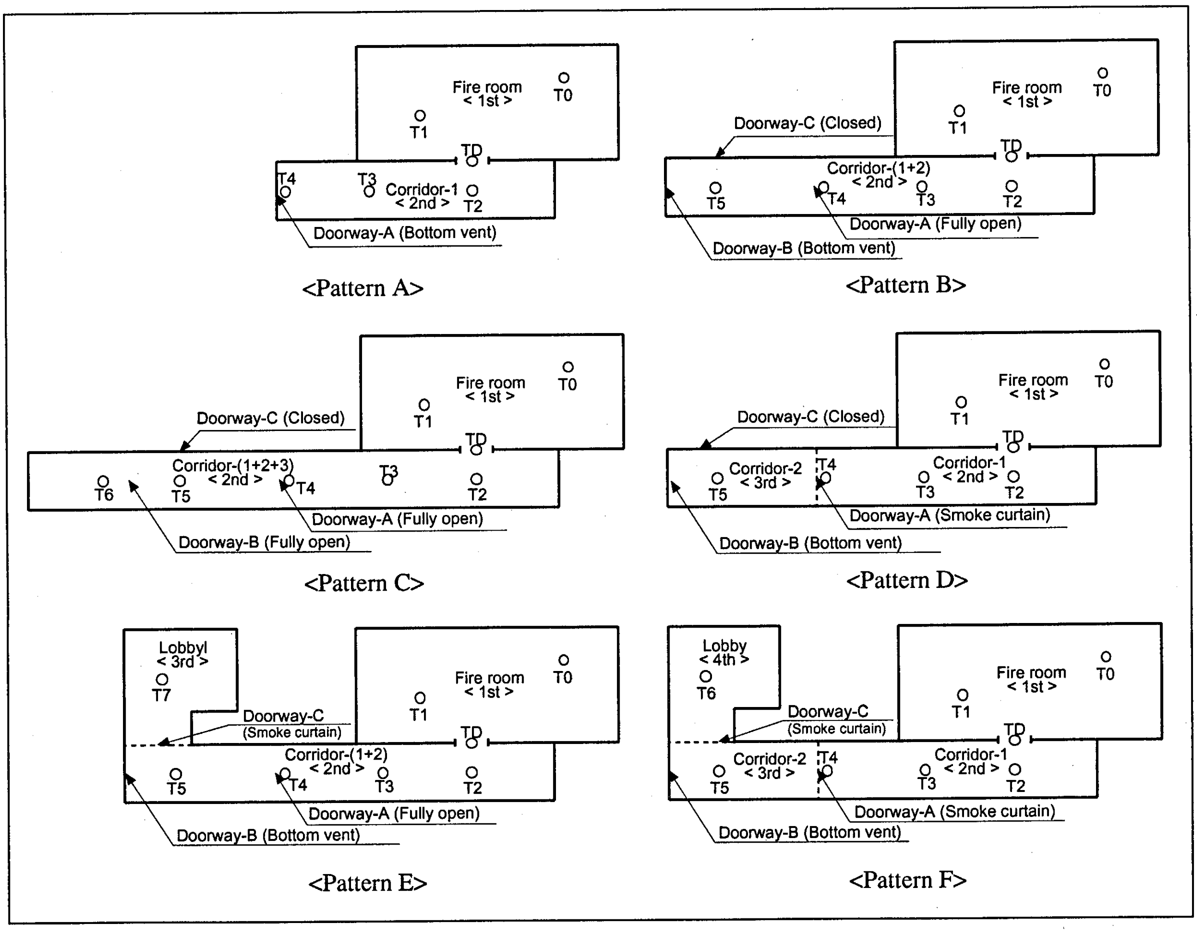

Figure 5 The arrangements of each experimental pattern

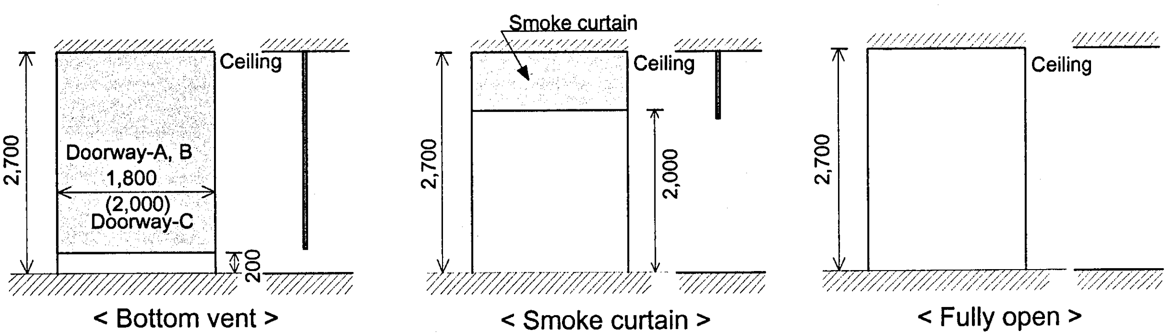

Figure 6 The schematic of doorway condition (unit: mm)

2.3 Smoke Temperature Measurements

To measure the smoke layer height and temperature, thermocouple trees are put in the locations shown in Figure 4. The tree has type-K thermocouples (0.3 [mm]-diam.). As shown in Figure 7, vertical temperature distribution was measured at by installing 14 thermocouples on each tree. Doorway smoke temperature profile was measured by 15 thermocouples (tree TD). The total number of thermocouples was 127.

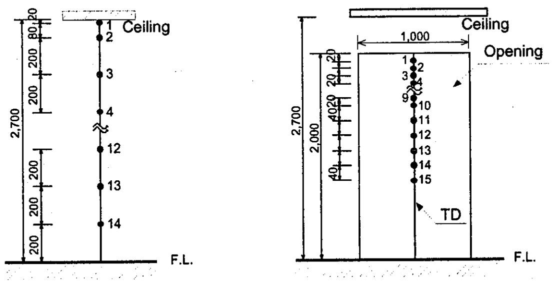

Figure 7 The schematic of the thermocouple trees (unit: mm)

3.RESULTS

3.1 Fire Growth Rate

As an example, measured HRR curve for exp. Pattern A is shown in Figure 8. The HRR could be well approximated by t^2-growth. The fire growth rate for this experiment was 0.0065 [kW/s²]. Also in the other experiments, the HRR is almost t-squared. The fire growth rates are summarized in Table 4. The range of scatter was 0.0079 to 0.0045 [kW/s²].

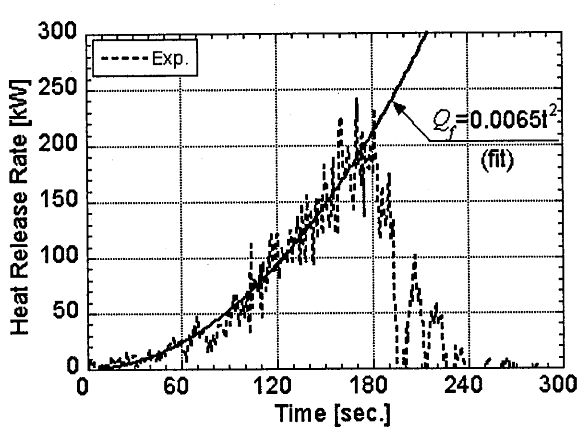

Figure 8 Heat Release Rate of the fire source (Pattern A)

3.2 Smoke Temperature (Pattern A - Fire Room with Small Corridor)

As an example, the results for experimental pattern A were described below. In Figures 9-14, vertical temperature distributions were shown for each tree. Figures 9 and 10 show the temperature profiles in the room of fire origin (T0 and T1) at every 30 seconds. In the fire room, the maximum temperature was 90 [℃] at 180 seconds after ignition. The slight difference between T0 and T1 are due to the difference in the distance from fire source.

At 120 seconds, the smoke layer descends to the top of the doorway opening. After that smoke starts to flow out to corridor. Even at 180 seconds, the temperature at 1m above floor is still close to initial temperature. This is due to the smoke flow out and air incoming through the doorway. This is also obvious in Figure 11, which shows the temperature profile at the doorway (TD).

The smoke temperature rise in the corridor is shown in Figures 12(T2), 13(T3) and 14(T4). Among them, the temperature rise in T2 is the largest and earliest. As the smoke flows beneath the ceiling, it mixes with air and lose heat to environment until reaching to T3 and T4. The temperature at T4 is similar to T3, however temperature at T4 is slightly higher at the end of fire. The slight difference is due to the collision of ceiling layers to the walls at the end of corridor. After collision, smoke accumulate downward around T4.

Table 4 Results of fire growth rate

Experimental pattern	A	B	C	D	E	F
Fire Growth Rate α [kW/s^2]	0.0065	0.0071	0.0056	0.0045	0.0079	0.0049

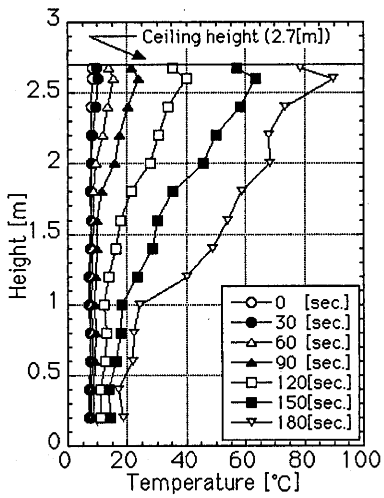

Figure 9 Vertical temperature distribution, T0 (Pattern A)

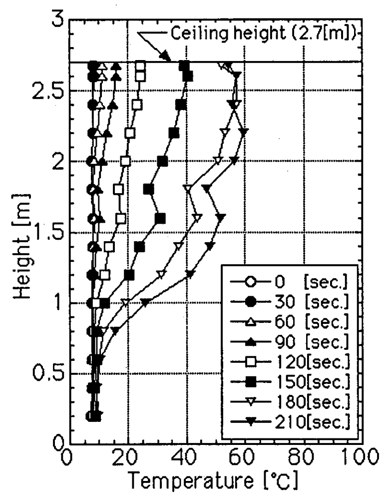

Figure 10 Vertical temperature distribution, T1 (Pattern A)

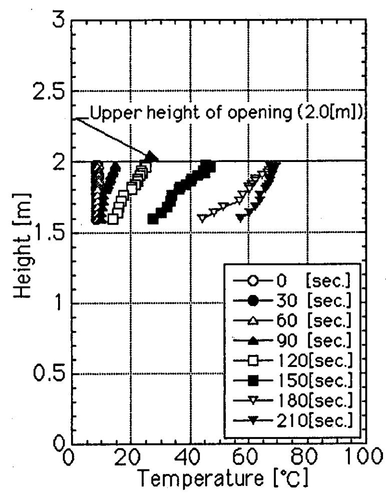

Figure 11 Vertical temperature distribution, TD (Pattern A)

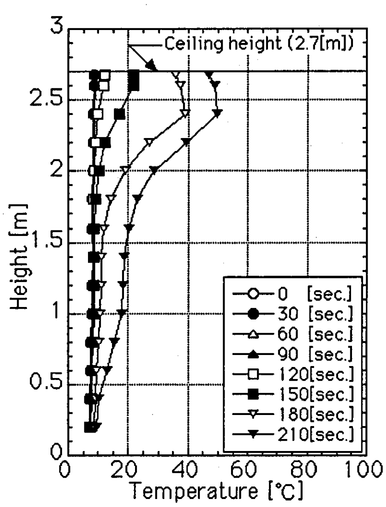

Figure 12 Vertical temperature distribution, T2 (Pattern A)

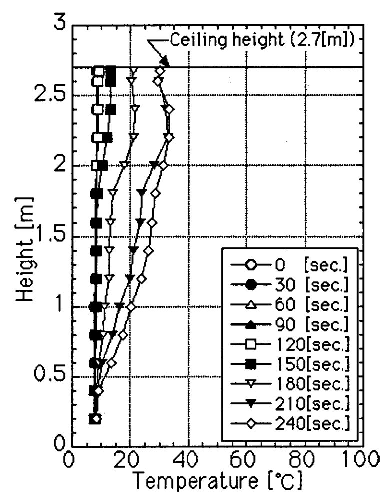

Figure 13 Vertical temperature distribution, T3 (Pattern A)

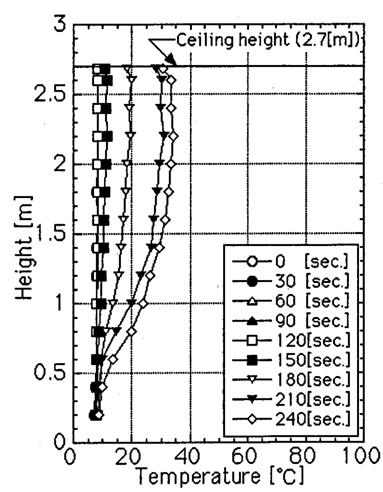

Figure 14 Vertical temperature distribution, T4 (Pattern A)

3.3 Smoke Layer Height and Average Smoke Temperature

Using the N-percent method [9] (N=10%) smoke layer height and average temperature were calculated for all the experimental results. Figures 15 to 20 show the results. In each set of figures, series (a) denotes the smoke layer height, (b) denotes the average temperatures.

(1) Fire Room

The smoke layer development in the room of fire origin is about 60 seconds after ignition (T0 and T1). After that the layer descends almost uniformly. After 120 seconds, the layer height close to the doorway (T1) is kept higher than that close to fire source (T0). This is because of the air inflow from corridor. After decay (180 seconds), smoke layer descends almost close to the floor (about 200 [mm] above floor at T0, 600 [mm] at T1). The above tendency is common to all the experimental patterns, which means that it is almost independent on the corridor size and arrangement.

(2) Corridor

Corridor smoke layer begins to develop at about 120 seconds. The rate of smoke layer development differs slightly depending on the size of corridor. In case of small corridor (pattern A), smoke layer descended quickly after 120 seconds. While, in case of large corridor (typically in patterns C and D) the development is relatively slow. It should be noted that there is a certain difference in smoke layer height in the corridor, especially in cases of large corridor. In case of pattern E, the difference in smoke layer development is about 30 seconds between the locations (T2 and T5).

The effect of smoke curtain is observed to delay the smoke propagate time to downstream corridors. This is obvious through the comparison between patterns E and F. In the pattern E, the lobby smoke developed at 150 seconds. While in the pattern F, the lobby smoke developed at 220 seconds. The difference is attributed to the smoke curtain at the doorway-A.

As a general tendency, the smoke layer declines right after the fire source has decayed. In all of the experiments, corridor smoke layer has declined to lower than 1 meter above floor. It means that the corridor is unsafe after combustion of three minutes unless some smoke management system is provided.

3.4 Enthalpy Release Rate to Corridor

Using the temperature measurement in the fire room, the enthalpy release rate to corridor Q_D [kW] was calculated by

$$Q_D = c_P \cdot m_D \cdot \Delta T_S \qquad (2)$$

where, c_P is the specific heat [kJ/kg.K], m_D is the mass flow rate through doorway [kg/s], ΔT_S is the smoke temperature rise of the fire room above ambient [K]. The mass flow rate through doorway was calculated by

$$m_D = \frac{2}{3} C_D B \sqrt{2 g \rho_S (\rho_\infty - \rho_S)} (H_D - S)^{3/2} \qquad (3)$$

where H_D is the doorway height[m], S is the smoke layer height in the room of fire origin[m], C_D is the flow coefficient [-], B is the doorway width [m], g is the gravity acceleration [m/s^2], ρ_S is the density of the smoke layer [kg/m^3], ρ_∞ is the ambient air density [kg/m^3]. Examples are shown in Figures 21 (Pattern A) and 22 (Pattern B, fire room to corridor 1, corridor 1 to corridor 2). In both cases, it is possible to fit delayed t^2-curve to represent the enthalpy release rate to downstream corridor

$$Q_D = \alpha' (t - t_0)^2 \qquad (4)$$

where α' is the equivalent fire growth rate [kW/s^2], t_0 is the delay time [s]. Thus there is a possibility to represent the virtual fire source of the corridor using the above formula. This type of data representation is beyond present analysis, thus we do not go further in this paper.

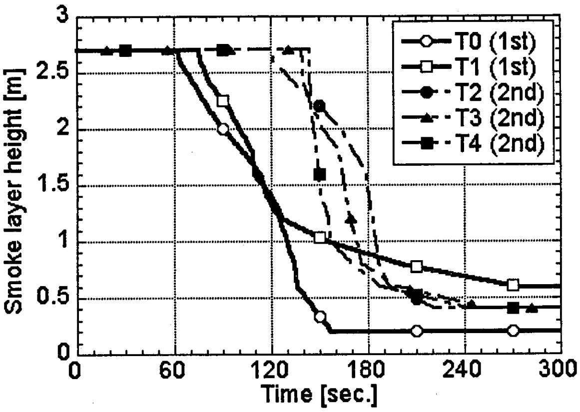

Figure 15(a) Smoke layer height (Pattern A)

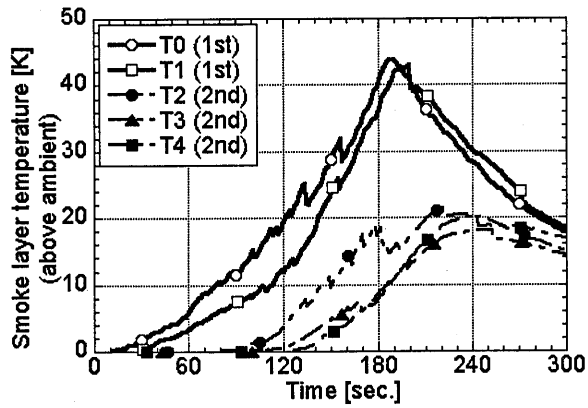

Figure 15(b) Smoke layer temp. (Pattern A)

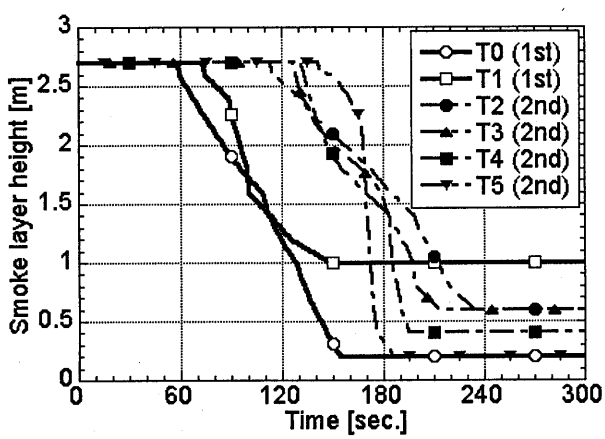

Figure 16(a) Smoke layer height (Pattern B)

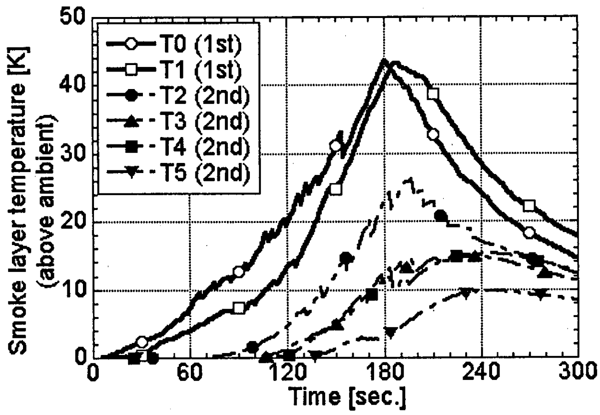

Figure 16(b) Smoke layer temp. (Pattern B)

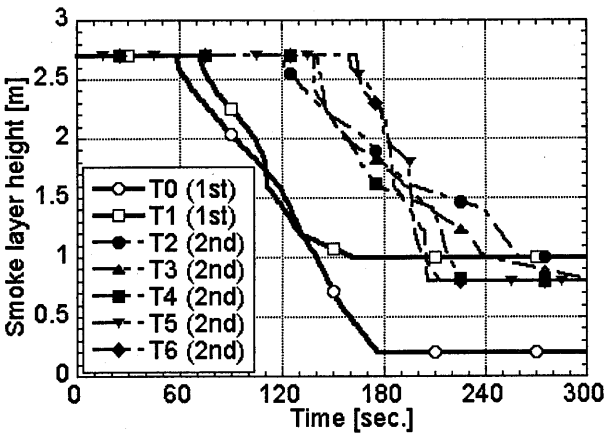

Figure 17(a) Smoke layer height (Pattern C)

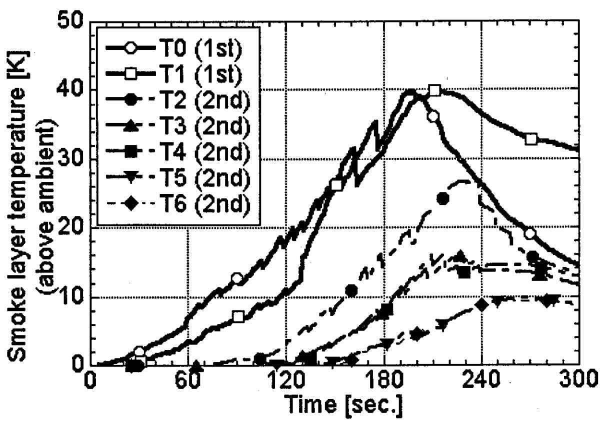

Figure 17(b) Smoke layer temp. (Pattern C)

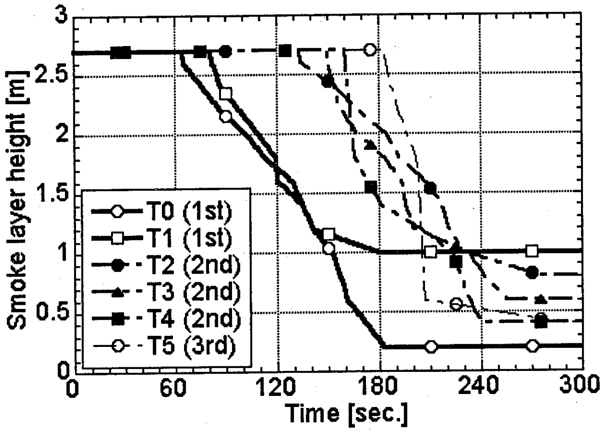

Figure 18(a) Smoke layer height (Pattern D)

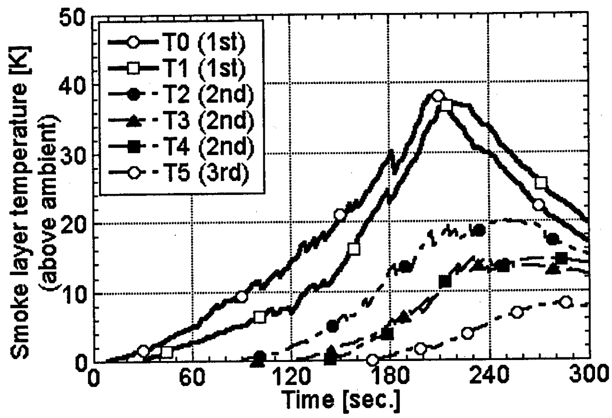

Figure 18(b) Smoke layer temp. (Pattern D)

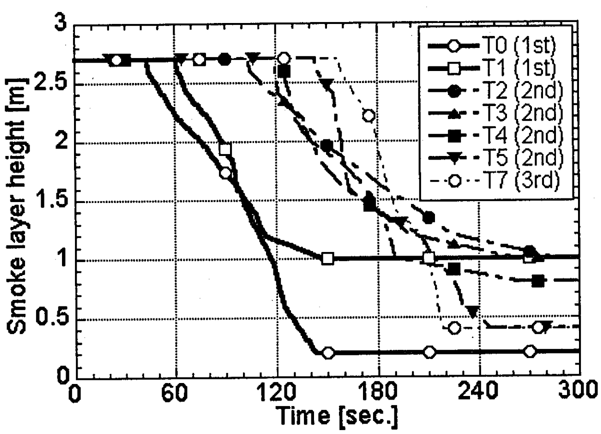

Figure 19(a) Smoke layer height (Pattern E)

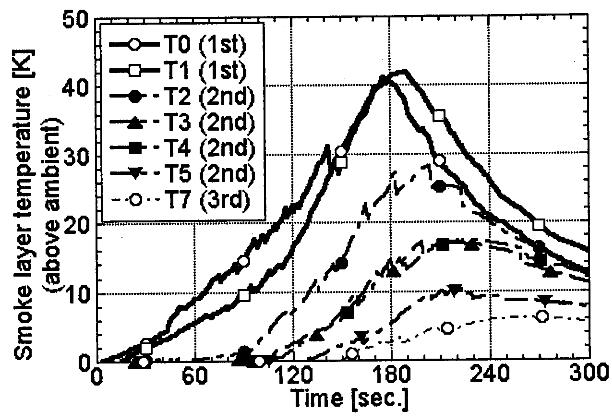

Figure 19(b) Smoke layer temp. (Pattern E)

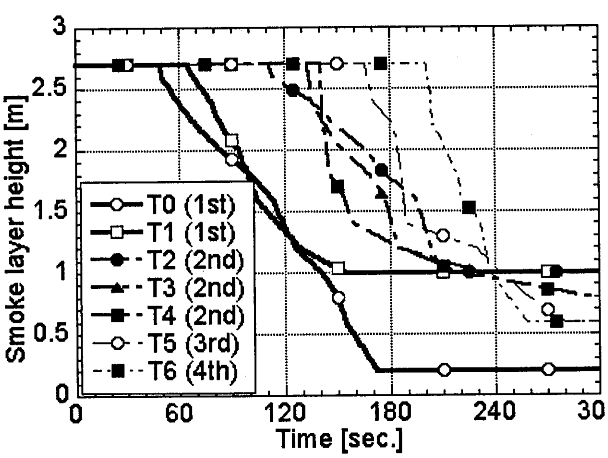

Figure 20(a) Smoke layer height (Pattern F)

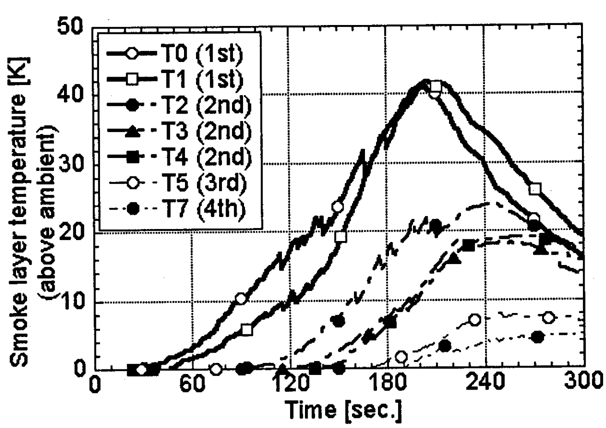

Figure 20(b) Smoke layer temp. (Pattern F)

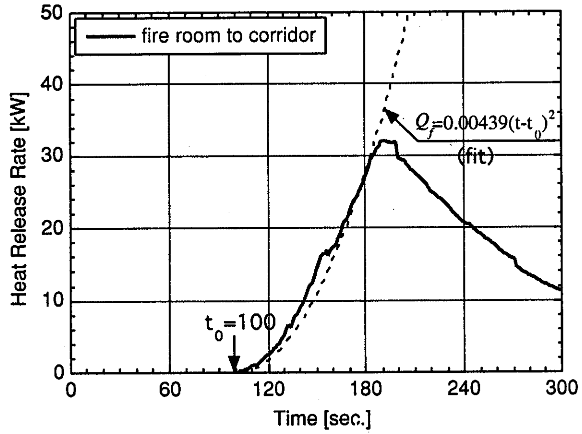

Figure 21 The enthalpy release rate to corridor (Pattern A)

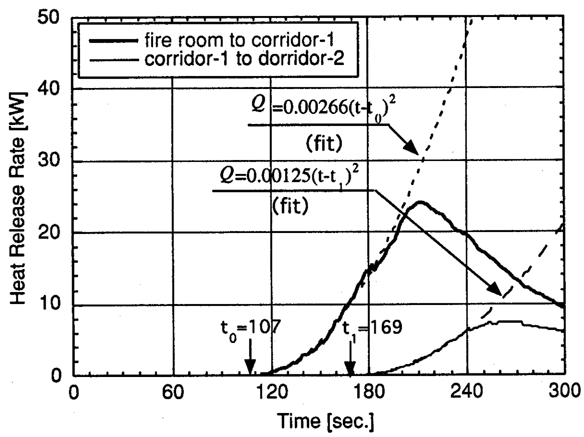

Figure 22 The enthalpy release rate to corridor (Pattern D)

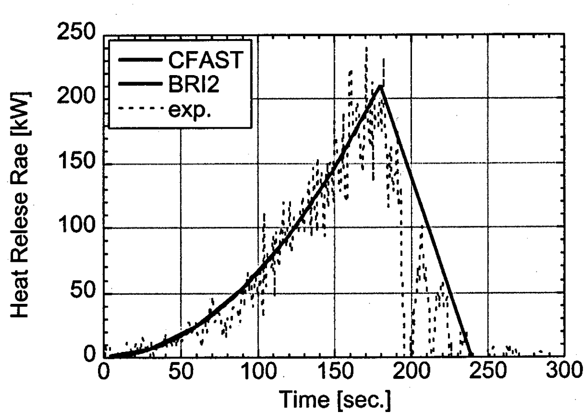

Figure 23 The input HRR curve (Pattern A)

4.Validation of Zone Models (BRI2 and CFAST) for t^2-fires.

4.1 Calculation

Two zone models, BRI2 and CFAST were selected to simulate the experimental realization. Among the experimental data, the conditions for Patterns A and B were selected and simulated by BRI2 and CFAST, respectively. The input HRR curve is shown in Figure 23.

4.2 Comparison Results

The calculated results are shown in Figures 24, 25 (Pattern A) and 26, 27 (Pattern B) in comparison with experimental data. Both of the two models predict faster smoke development both in cases of Patterns A and B. As to the temperature, model predictions are slightly higher than the maximum temperature of the smoke layer. In this sense, the models are valid to use in engineering design purpose.

However, the post decay behavior is not well predicted by zone models. After decay, the model prediction gives the decrease of smoke layer temperature. At the same time, the thermal shrinkage of smoke layer seems to be predicted. As a result, smoke layer height is increased after decay. This difference is clear in case of BRI2 predictions. In experiment, there is a considerable "mixture" between smoke layer and air layer at the cooling stage. Thus the smoke layer quickly descends to floor level. In an engineering viewpoint, this difference might mislead fire engineers. Thus there is a need to revise zone model codes to include mixing of less buoyant smoke with lower air layer.

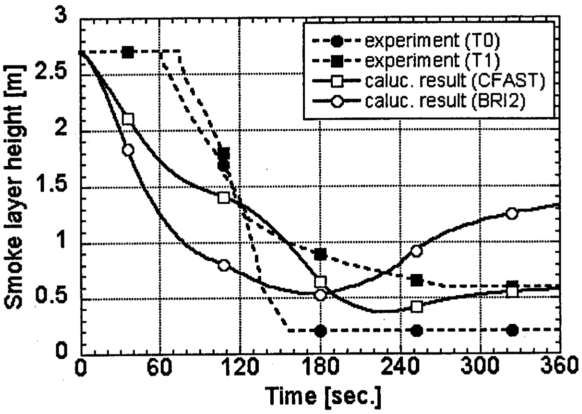

Figure 24(a) Smoke layer height of the fire room (Pattern A)

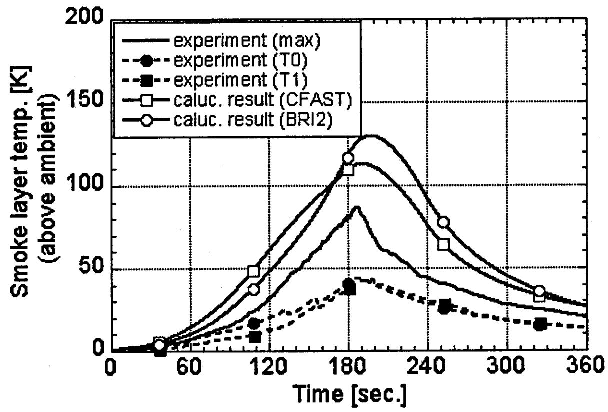

Figure 24(b) Smoke layer temp. of the fire room (Pattern A)

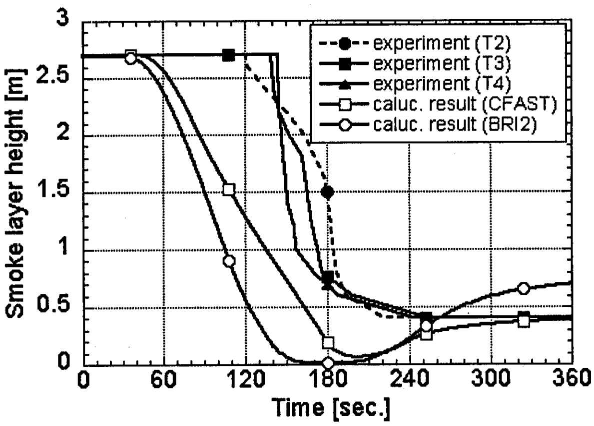

Figure 25(a) Smoke layer height of the corridor-1 (Pattern A)

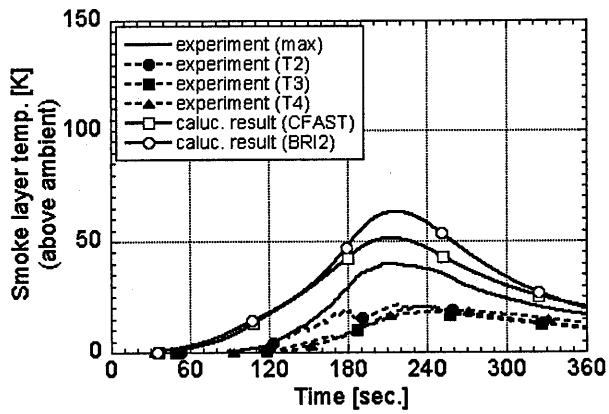

Figure 25(b) Smoke layer temp. of the corridor-1 (Pattern A)

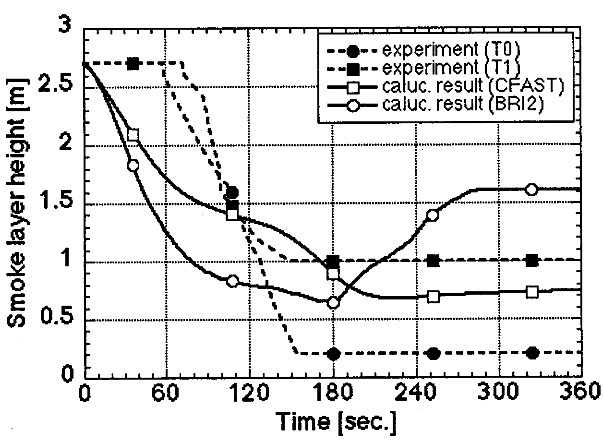

Figure 26(a) Smoke layer height of the fire room (Pattern B)

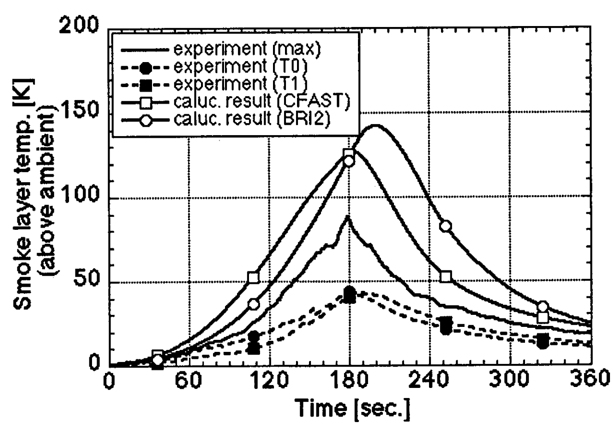

Figure 26(b) Smoke layer temp. of the fire room (Pattern B)

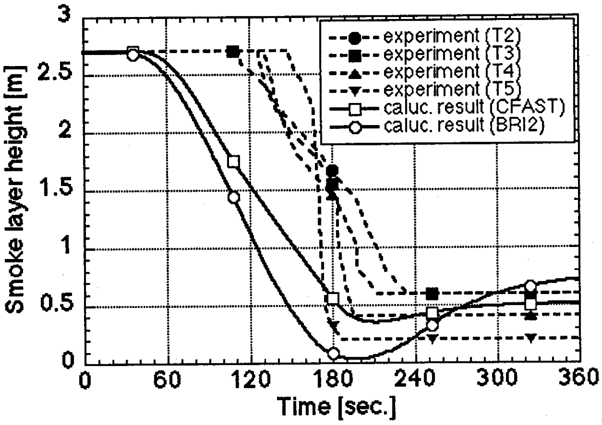

Figure 27(a) Smoke layer height of the corridor-1 (Pattern B)

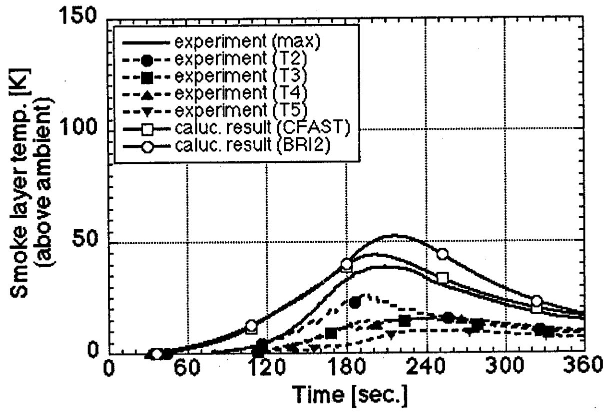

Figure 27(b) Smoke layer temp. of the corridor-1 (Pattern B)

5.CONCLUSION

A series of full scale experiments were carried out to investigate the smoke propagation behavior for t^2-fires. The effects of corridor arrangement (size and smoke curtains) were analyzed. The corridor size and smoke curtains have beneficial effect to delay the smoke propagation to downstream corridors. In the experiments, quick mixing of smoke after the decay of fire was observed that results in blockage of corridors. In the prediction of smoke layer by using zone models, this effect is not taken into account. Thus there is a need to revise zone type equations to include smoke-air mixing during post decay period.

ACKNOWLEDGMENTS

The authors would like to thank Mr. N., Nakamura and Mr. Y., Misawa (Formerly Graduate student, Science Univ. of Tokyo) for fully support of this experiment.

NOMENCLATURE

B : doorway width [m]
C_D : flow coefficient [-]
c_P : specific heat [kJ/kg.K]
g : gravity acceleration [m/s^2],
H_D : doorway height [m]
m_D : mass flow rate through doorway [kg/s]
Q_f : design Heat Release Rate [kW]
S : smoke layer height in the room of fire origin [m]
ΔT_S : smoke temperature rise of the fire room above ambient [K]
t : time from ignition [sec.]
t_0 : delay time [s]
α : fire growth rate [kW/s2]
α' : equivalent fire growth rate [kW/s^2]
ρ_S : density of the smoke layer [kg/m^3]
ρ_∞ : ambient air density [kg/m^3]

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