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EXPERIMENTAL STUDY ON SMOKE MOVEMENT IN ATRIUM DURING FIRE USING SCALE-MODEL

Makoto Tsujimoto, Dr.Eng.
Nagoya University
Nagoya, Japan

Masaya Okumiya, Dr.Eng.
Chubu University
Kasugai, Japan

SUMMARY

The method to predict the smoke movement in atrium during fire using reduced scale model is presented. In this method, it is necessary that the similarity is established, so the scaling law to secure the similarity and the results of the experiments according to the scaling law are also presented.

The scaling law was derived by dimensional analysis of the governing equations (continuity, conservation of momentum and conservation of energy) and the boundary condition at the flames and the wall.

Experiments were conducted in two stages. At first, the similarity was examined by the experiments using two kind of reduced model (1/10 and 1/25 model). The temperature profile and the visualized smoke movement of two models were compared and it was confirmed that the phenomena took place in almost similar manner.

Then, comparison of the phenomena in real scale and reduced scale model was carried out and the similarity was also confirmed.

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INTRODUCTION

Recent years a number of buildings including a large atrium have been constructed in Japan. Such a large space in a building is open, therefore very attractive in design, and becomes public space because various people utilize it. So, it is necessary to confirm the safety in such a space and from the standpoint of fire safety engineering, it is necessary to develop a method to estimate the smoke movement in the atrium.

Several methods have been studied for predicting the movement of smoke during a fire. However, this phenomenon is turbulent natural convection and it is difficult to obtain a solution analytically. Then in the present paper we shall try to predict the smoke movement in atrium by using a scale-model.

If the smoke movement in the atrium is considered to be governed primarily by the fire plume, the scaling law can be selected from the study by Quintiere[1]. Because the phenomenon is unsteady, however, only a few experiments, for example, Emori's[2], show the validity of the scaling law.

To begin with, experiments were conducted using two models of which scale ratio is 2.5. Results of two different scale model (vertical temperature profile) were compared by adjusting the elapsed time with scaling law. Secondary experiments were carried out using one-fortieth model of the actual building in which large space is included and results were compared in the same manner.

In addition to the measurement of temperature, smoke movement was visualized using lazer light sheet.

SCALING LAW

The topic chosen here is heat flux and air flow in the atrium. As these phenomena are unsteady, the scaling law is the conditions under which the elapsed time for diffusion of heat and flow is similar. Then, the scaling law is drived from the π-parameters which are deduced by dimensional analysis of governing equations (continuity, conservation of momentum and conservation of energy) and the boundary conditions.

Governing equations can be written to the equations (1)~(3) based on the following assumptions.

- neglect of the diffusion of mass
- assumption of incompressible fluid and bussinesq approximation
- modeling of Reynalds stress and heat transfer using eddy kinematic viscosity and heat transfer coefficient
- neglect of the energy dissipation

$$\frac{\partial \overline{u_i}}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial \overline{u_i}}{\partial t} + \overline{u_j}\frac{\partial \overline{u_i}}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \overline{p}}{\partial x_i} + g_i\beta(\overline{\theta} - \theta_0) + \nu_t\frac{\partial^2 \overline{u_i}}{\partial x_j \partial x_j} \tag{2}$$

$$\rho c_p \left(\frac{\partial \overline{\theta}}{\partial t} + \overline{u_i}\frac{\partial \overline{\theta}}{\partial x_i}\right) = \rho c_p \alpha_t \frac{\partial^2 \overline{\theta}}{\partial x_i \partial x_i} + q \tag{3}$$

where u_i and u_j are velocity vector, ρ is density, p is pressure, g_i is gravity acceleration vector, β is the coefficient of thermal expansion, θ is temperature, ν_t is the eddy kinematic viscosity, c_p is specific heat under constant pressure, α_t is the eddy heat transfer coefficient, and q is rate of heat generation.

Then, the above equations (eq.(1)~(3)) can be made dimensionless by introducing following normalizing parameters and accompanying dimensionless variables:

• normalizing parameters

$$\left.\begin{array}{l}
\text{characteristic length, } L_0 \\
\text{characteristic velocity, } u_0 \\
\text{characteristic time, } t_0 \\
\text{characteristic heat generation rate, } Q_0 \\
\text{characteristic temperature difference and ambient temperature, } \Delta\theta_0, \theta_a \\
\text{characteristic pressure difference and ambient pressure, } \Delta p_0, p_a
\end{array}\right\} \tag{4}$$

• dimensionless variables

$$\left.\begin{array}{ll} L^* = L/L_0 & \\ u_i^* = \overline{u_i}/u_0 & \\ Q^* = qL_0^3/Q_0 & \\ t^* = t/t_0 & \\ \Delta\theta^* = \overline{\Delta\theta}/\Delta\theta_0, & \overline{\Delta\theta} = \overline{\theta} - \theta_a \\ \Delta p^* = \overline{\Delta p}/\Delta p_0 & \overline{\Delta p} = \overline{p} - p_a \end{array}\right\} \quad (5)$$

$$\frac{\partial u_i^*}{\partial x_i^*} = 0 \quad (6)$$

$$\frac{L_0}{t_0 u_0}\frac{\partial u_i*}{\partial t^*} + u_j^*\frac{\partial u_i^*}{\partial x_j^*} = -\frac{\Delta p_0}{\rho u_0^2}\frac{\partial p^*}{\partial x_i^*} + g_i\beta\frac{\Delta\theta_0 L_0}{u_0^2}\Delta\theta^* + \frac{\nu_t}{L_0 u_0}\frac{\partial^2 u_i^*}{\partial x_j^*\partial x_j^*} \quad (7)$$

$$\frac{L_0}{t_0 u_0}\frac{\partial\theta^*}{\partial t^*} + u_i^*\frac{\partial\theta^*}{\partial x_i^*} = \frac{\alpha_t}{L_0 u_0}\frac{\partial^2\theta^*}{\partial x_i^*\partial x_i^*} + \frac{Q_0}{\rho c_p u_0 \Delta\theta_0 L_0^2}Q^* \quad (8)$$

And following four dimensionless variables (π's) are given.

$$\left.\begin{array}{l} \pi_1 = \dfrac{L_0}{t_0 u_0} \\ \pi_2 = \dfrac{\Delta p_0}{\rho u_0^2} \\ \pi_3 = g_t\beta\dfrac{\Delta\theta_0 L_0}{u_0^2} \\ \pi_4 = \dfrac{Q_0}{\rho c_p u_0 \Delta\theta_0 L_0^2} \end{array}\right\} \quad (9)$$

In deriving above π-parameters, ν_t/L_0u_0 and α_t/L_0u_0 are considered as constant because the flow is turbulent[3]. Since there are four equations for six normalizing parameters, four of them $(u_0, Q_0, t_0, \Delta p_0)$ can be represented by the remaining two $(L_0, \Delta\theta_0)$. Further, in the case that the same kind of heat source is used in different scale-models, that is, in the case where the temperature difference between flames and ambient is equal, $(\Delta\theta_M/\Delta\theta_R)$ becomes unity on the boundary. Consequently the similarity law is as follows;

$$\left.\begin{array}{l} n(Q) = \left[\dfrac{Q_M}{Q_R}\right] = \left[\dfrac{L_M}{L_R}\right]^{5/2} = n(L)^{5/2} \\ n(t) = \left[\dfrac{t_M}{t_R}\right] = \left[\dfrac{L_M}{L_R}\right]^{1/2} = n(L)^{1/2} \\ n(u) = \left[\dfrac{u_M}{u_R}\right] = \left[\dfrac{L_M}{L_R}\right]^{1/2} = n(L)^{1/2} \\ n(\Delta p) = \left[\dfrac{\Delta p_M}{\Delta p_R}\right] = \left[\dfrac{L_M}{L_R}\right] = n(L) \end{array}\right\} \quad (10)$$

where subscripts R and M stand for real scale and model, respectively.

BOUNDARY CONDITION

As shown in the process of deriving the scaling law, $n(\Delta\theta) = 1$ is assumed. The similarity of the shape and characteristics of the flame, and the ratio of the heat absorbed by the wall to the heat flux of smoke lawer were considered as the boundary condition.

Similarity of flame

Configuration of fire frame is represented as equation (11)[4].

$$\left.\begin{aligned} \frac{L_f}{D} &= f(Q_f^*) \\ Q_f^* &= \frac{Q}{D^{5/2}} \end{aligned}\right\} \tag{11}$$

where L_f and D are height and diameter of flame and Q is released heat rate.
If $n(Q) = n(L)^{5/2}$ is satisfied, then

$$n(Q_f^*) = \frac{n(Q)}{n(D)^{5/2}} = \frac{n(L)^{5/2}}{n(D)^{5/2}} \tag{12}$$

Therefore if $n(D)$ is equal to $n(L)$, $n(Q_f^*)$ becomes unity. In other words, if the heat generation rate Q is controlled as $n(Q) = n(L)^{5/2}$ and the diameter of flame D is similar to L, the configuration of the flame becomes similar.

Selection of material of wall

Simplifying the mechanism of surface heat transfer, the surface temperature of the wall is considered to be equal to the smoke layer. The condition that the heat absorbed by the wall is proportional to $Q \times t$ gives following equation;

$$n(\lambda_W \rho_W c_W) = \left[\frac{(\lambda_W \rho_W c_W)_M}{(\lambda_W \rho_W c_W)_R}\right] = \left[\frac{L_M}{L_R}\right]^{3/2} = n(L)^{3/2} \tag{13}$$

Where λ_W is heat conductivity, ρ_W is density and c_W is specific heat of the wall.

EXPERIMENTAL SETUP

Model

1. Experiment for comparison between reduced scale models.

   The scale length were determined on the supposition that the atrium is five stories high. Two scale modeles, 1/25, 1/10, were used in the experiments. Figure 1 shows the plan and cross section of the models. Material of the wall was selected according to equation (13). It suggests that a concrete wall in real scale corresponds to cork in 1/25 scale, and ceder in 1/10 scale. So the wall of the models were made of cork and hard board, respectively.

2. Experiment for comparison between actual and reduced scale models.

   In this series of experiments, the similarity law is valided by comparison between results of actual and reduced models. The building chosen as the subject of study is the former KOKUGIKAN SUMO HALL and reduced model is 1/40 of it. Figure 2 shows plan and cross section. Wall and roof of the reduced model was made of veneer and rock wool, respectively.

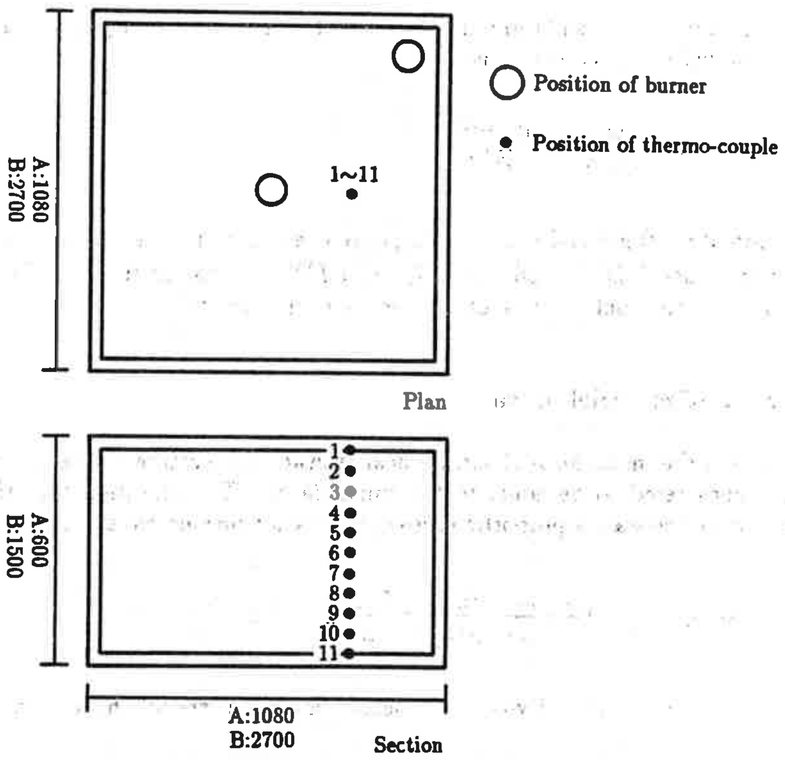

Fig.1 Plan and section of modeles (A:1/25, B:1/10)

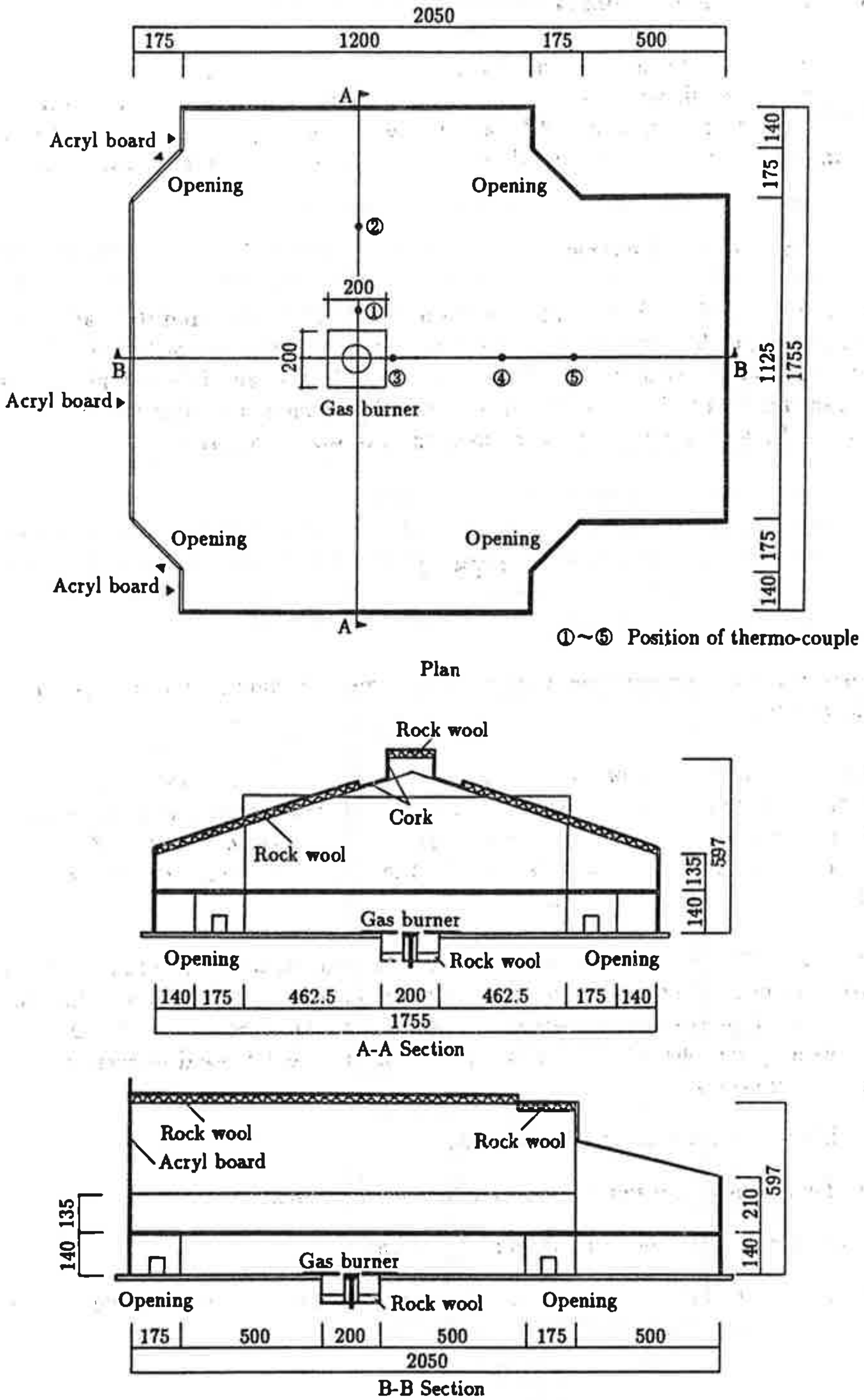

Fig.2 Plan and cross section of the reduced model of the former KOKUGIKAN SUMO HALL

Measurement and visualization

The temperatures in the space and openings were measured by CC thermo-couples at the points as shown in Figure 1 and 2. The smoke movement was visualized by the argon lazer light sheet (4W) and it was recorded by photographs and video system. So, one face of the reduced model was made of the transparent acryl board.

Flames and smoke generator

The diameter of the fire in a real scale was assumed to be 1.5m, and the glass funnel stuffed with small stones was used as a burner. The diameter of the burner was determined by the scale ratio. Propane was used as fuel and it was controlled by the mass flow controller. As combustion gas of propane is too clear to visualize, a smoke ball made of gunpowder and small chips of wood was used.

RESULTS

Comparison of the temperature and the smoke movement of the reduced scale models

Figure 3 shows the comparison of the change of the vertical temperature profile of Series A (scale 1/25) and Series B (scale 1/10) experiment. The temperature was measured every 10 seconds (Series A) or every 16 seconds (Series B). In the experiments, heat release rate was controlled in steps. The height of the lower end of smoke layer is plotted in Figure 3.

From Figure 3, it can be concluded that the vertical tempereture profile and the smoke movement of both series of experiment are almost similar. However, the temperature of the smoke layer in Series B is higher than that in Series A and $n(\Delta\theta) = 1$ is not exactly established as a result. It is considered that these disagreements are cause by followings.

- difference of mechanism of radiation
- effect of heat transfer between smoke layer and surface
- change of combusion mechanism of propane
- effect of energy related to Ec number which is not conserved as scale changes

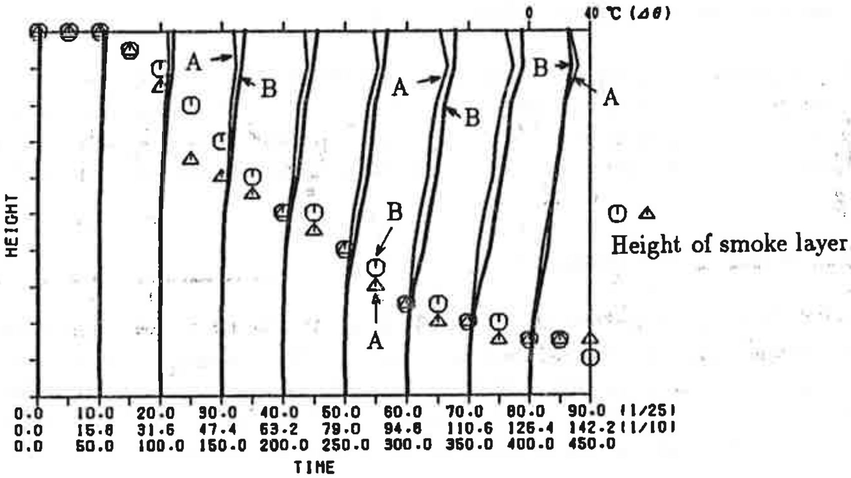

Fig.3 Comparison of the vertical temperature profile and the smoke movement of the reduced scale models

Comparison of the phenomena between real and reduced scale model

Figure 4 shows the change of the vertical temperature profile of the actual building and the reduced model experiments. The temperature in actual building was mesured at the former KOKUGIKAN SUMO HALL in 1984 just before it was destroyed and the data was offered by the Tokyo Metropolitan Fire Board. The temperature was measured every 9 seconds in the reduced model (1/40) experiments and it corresponds to 1 minute in the real scale. In the experiments conducted at KOKUGIKAN, about 600kg of cloths was burned as fire source and it's weight change is shown by a solid line in Figure 5. In the case of the reduced model experiments, the heat released rate is approximated as shown in Figure 5.

The temperature profile in both scale experiments shows good agreement at the position far from flames (Figures 4(b),4(d),4(e)), except that the temperature in the actual scale experiment is slightly higher than that in the reduced model at the upper part. In the actual scale experiments, however, high temperatures were measured when heat released rate was large (the elapsed time from 3 to 9 minutes) at the position near the flames (Figures 4(a),4(c)), therefore remarkable disagreement between actual and reduced model was observed. It may be due to the radiation from flames which effected the thermo-couple especially in the case of the heat release rate being large and the complex flow near the flames just after ignition.

Figure 6 shows the smoke movement in the reduced model visualized by the argon lazer light sheet. The thickness of the smoke layer measured in the actual scale experiment is shown in Figure 7. From comparison of these results, the smoke layer in the reduced model grew faster than that in the actual model.However, the difference is negligible and the experimental method using the reduced model is effective for predicting the smoke movement in the atrium.

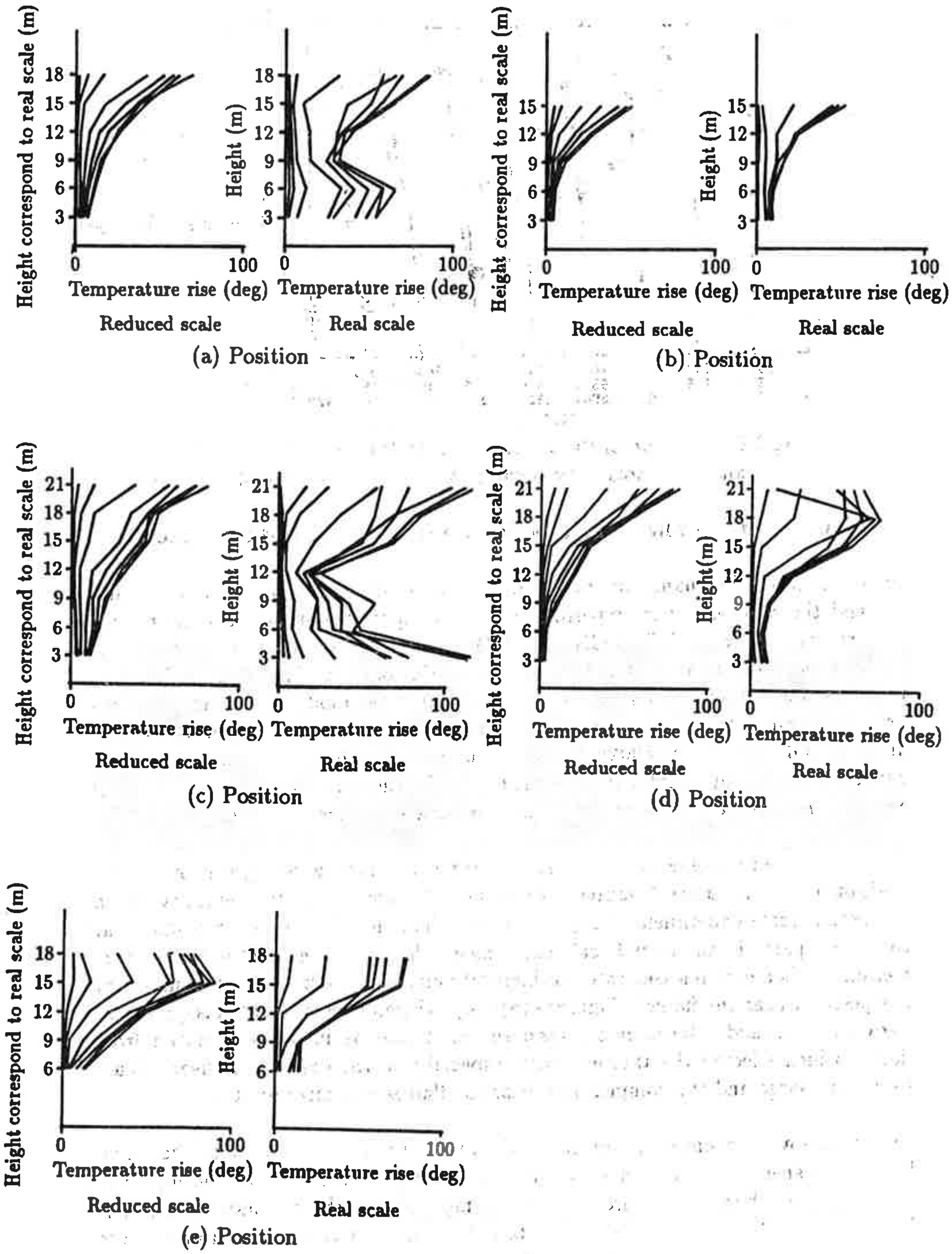

Fig.4 Vertical temperature profiles

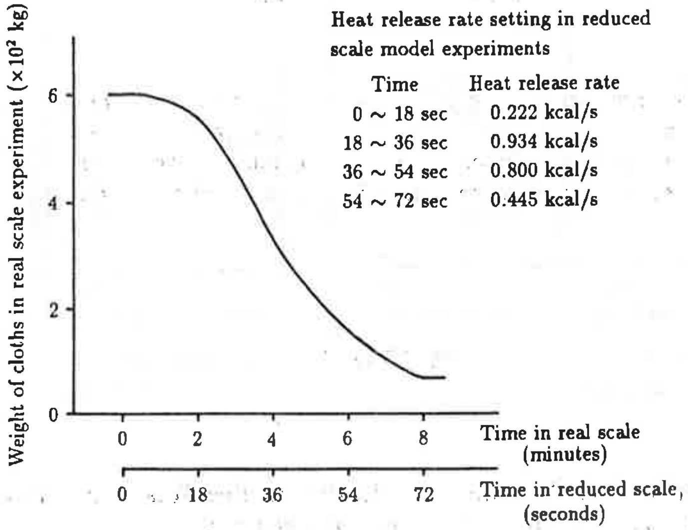

Fig.5 Experimental condition of heat release rate

(a) 27 seconds (b) 36 seconds

Fig.6 Visualization of smoke movement in reduced scale model

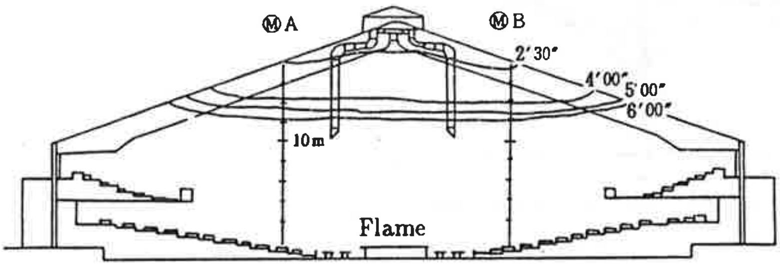

Fig.7 Smoke movement in real scale model

ACKNOWLEDGEMENT

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