A SCALING LAW OF SMOKE MOVEMENT IN ATRIUM

Makoto Tsujimoto, Tetsuji Takenouchi
Faculty of Engineering
Nagoya University
Furo-cho, Chikusa-ku, Nagoya, Japan
Shigeo Uehara
Building Design Department, Tokyo Main Office
Takenaka Corporation
8-21-1, Ginza, Chuo-ku, Tokyo, Japan

ABSTRACT

An experimental verification on a scaling law of smoke movement in an atrium was performed using the models of 1/25 and 1/10 scale. In accordance with the scaling law , which requires that heat release rate and time are proportional to 5/2th power and 1/2th power of representative length, respectively, the movement and the temperature profile of smoke layer became similar.

1. INTRODUCTION

These days the number of buildings which have a large atrium space is growing in Japan. And some of them are designed without barriers between atrium space and its surrounding area. So, from a standpoint of fire safety engineering, it is necessary to develop a method to estimate the unsteady smoke movement in the atrium.

One of the methods is to confirm the scaling law governing the smoke movement in the compartment, and to make small scale experiments according to the scaling law. 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.

In this study, two different scale model, 1/10 and 1/25 were used to investigate it. Although, according to the scaling law, the heat release rate of these two models differs about 10 times, the pictures of the smoke movement visualised by lazer light sheet proved the validity.

2. SCALING LAW

The atrium which we deal with in this study is five stories height, and its plan and sketch are shown in Fig.1 and Fig.2. And the ultimate purpose of this study is to estimate the smoke movement by small scale experiments under the various condition of openings, for example, changing the position and the size of the openings between the atrium and the outside air, the ones of elevator shafts between each atrium etc., to avoid the condition in which people in evacuation become in danger. Because the present object of this study is to confirm the scaling law, the condition of the openings of the model was simplified.

As the smoke movement in an atrium is considered to be a phenomenon of heat convection governed by the fire plume, using the classical dimensional analysis, we can derive the dimension of length $[L]$ and time $[t]$ as a function of the variables (Q, C_p, T_0, ρ_0 and g), the combination of which explains the velocity or temperature of the free boundary fire plume.

$$[L] = \left(\frac{Q^2}{g\rho_0^2 C_p^2 T_0^2}\right)^{\frac{1}{5}} \qquad [t] = \left(\frac{Q}{g^3 \rho_0 C_p T_0}\right)^{\frac{1}{5}} \tag{1}$$

where Q:heat release rate, C_p, T_0, ρ_0:specific heat, absolute temperature, and density of ambient air, respectively, g:gravity acceleration

If the heat release rate in real scale and reduced scale are given, these equations are rewritten as follows;

$$\frac{Q_M}{Q_R} = (\frac{L_M}{L_R})^{\frac{5}{2}}$$

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

where subscripts M and R mean model and real scale, respectively.

The same relation was derived by Quintiere[1)] using the Froude modeling and the Boussinesq assumption. If the heat transfer by radiation and between smoke layer and the wall of atrium is neglected, the temperature rise of smoke($\Delta\theta$) becomes independent of scale as follows;

$$\frac{\Delta\theta_M}{\Delta\theta_R} \simeq \frac{Q_M t_M / L_M^3}{Q_R t_R / L_R^3} = 1 \tag{3}$$

3. EXPERIMENT

A series of experiments was performed under following conditions.

1) length scale

Two scale models, 1/25, 1/10, were used in the experiments. Fig.5 shows the plan and cross-section of the models.

2) material of wall

If the materials of the wall were selected in such condition that heat transfer from smoke layer to the wall is propotional to $Q \cdot t$ in equation(3), $\Delta\theta$ becomes independent of scale.

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 to the wall is proportional to $Q \cdot t$ gives following equation ;

$$\frac{(\lambda_s \rho_s C_s)_M}{(\lambda_s \rho_s C_s)_R} = (\frac{L_M}{L_R})^{\frac{3}{2}} \tag{4}$$

λ_s, ρ_s, C_s : thermal conductivity, density, specific heat of the wall

It suggests that a concrete wall in real scale corresponds to cork in 1/25 scale, and cedar in 1/10 scale. So the walls of the models were made of cork and hard board, respectively.

3) heat source

The diameter of fire in real scale was assumed to be 1.5m, and the glass funnel stuffed with small stones was used as a burner. Propane was used as fuel.

4) smoke generator

As combustion product gas of propane is too clear to visualize, a smoke ball made of gunpowder and small chips of wood was used. The position of the smoke ball was selected for generated smoke to mix into the upward flow of plume.

5) variables

The experiments were performed, by changing the size of openings, heat release rate, and the position of the burner. The conditions of standard experiments are listed in Table.1. The values of Table.1 showes real scale ones, and in Series A (scale 1/25) and Series B(scale 1/10), the values were determined according to equations(2).

6) measurement

The temperatures in the compartment and at the openings were measured by 0.65ϕ CC thermo-couples every 10 seconds (Series A) or every 16 seconds (series B). The smoke layer visualized by the argon lazer light sheet (4W) was recorded by photographs and a video system.

4. RESULTS

To confirm the scaling law, the results of experiments in Series A and B are compared with in regard to the following two characteristics.

1) transient change of temperature profile; for example, the vertical temperature profiles in experiment 1-5, 2-5, 5-2 are shown in Fig.5-1 $\sim$ 5-3.

2) transient change of visualized smoke layer; video pictures of experiments in Series A which are played back slowly in 63% ($1/\sqrt{2.5}$) speed are compared with the corresponding ones in Series B using two CRTs at the same time. And the comparison of the photos shown in Fig.6, as an example, is performed.

After these comparisons, it is concluded that both the profile of temperature and the movement of smoke layer are similar among Series A and B, except that the temperature of smoke layer in Series B is higher than that in Series A when the atrium has no opening (No.1-4 $\sim$ 1-6).

In this series of experiments, unexpected phenomena were observed. Before starting the experiments, the position of the burner was planned to be placed in center of the atrium such as No.3-1 $\sim$ 3-3 in Table.1. But the fire in that condition generated a fire whirl, and the smoke layer was too disturbed to be compared with as was shown in Fig.7. The fire whirl was observed in both series. So the position of the burner was changed to the corner where the fire whirl was not generated.

Another phnomenon observed is that the depth of smoke layer at the openings differs like Fig.5-3 because geometrical relations between the burner and the two openings are different.

One should note that these two phenomena cannot be explained by the two-zone model.

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1) Quintiere, J.G., "Scaling Application in Fire Research", Proc. of the International Symposium on Scale Modeling, 1988

2) Emori, R.I., Saito, K., "A Study of Scaling Law in Pool and Crib Fires", Combustion Science and Technology, Vol.31, pp.217–231, 1983

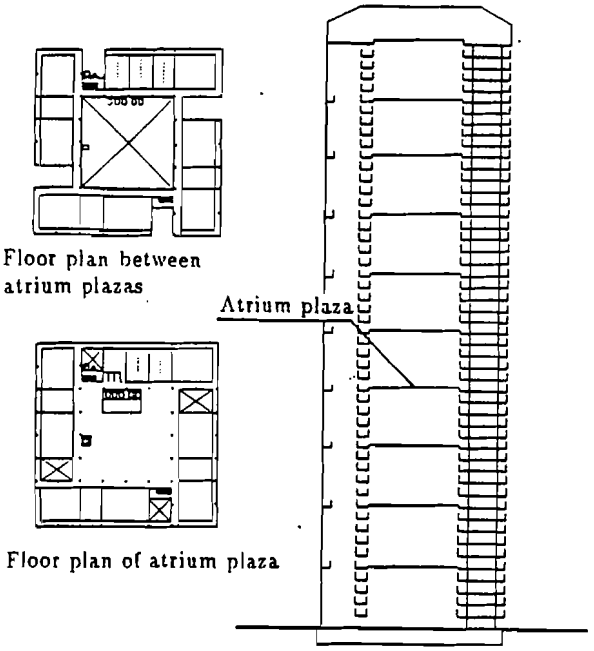

Fig.1 Plans and section of a high-rise apartment which has atriums every five stories

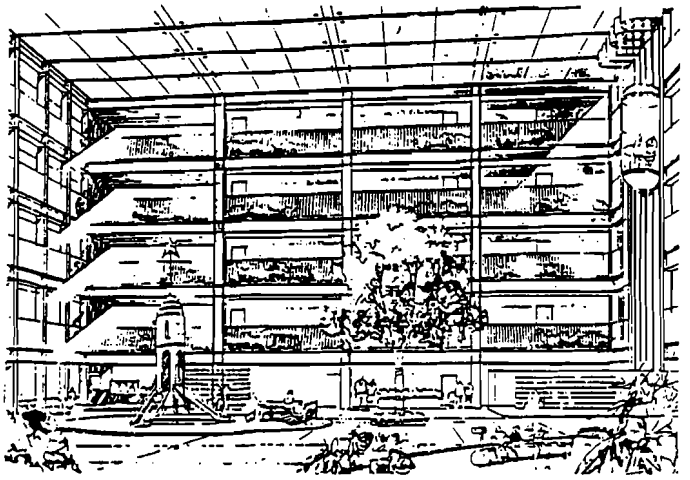

Fig.2 A perspective drawing of an atrium space

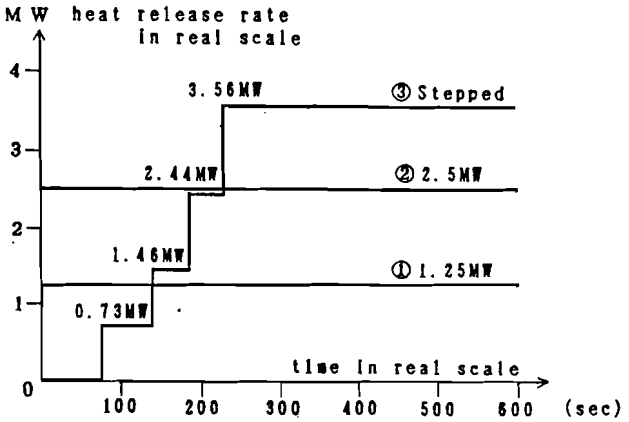

Fig.3 Experimental conditions of heat release rate

Table.1 Experimental conditions

No.	Opening (see Fig.4)	Position of burner (see Fig.4)	Heat release rate (see Fig.3)
1-4	No opening	Corner	1.25MW
1-5	〃	〃	2.5 MW
1-6	〃	〃	Stepped
2-4	W=2250,H=0	Corner	1.25MW
2-5	〃	〃	2.5 MW
2-6	〃	〃	Stepped
3-1	W=2250,H=0	Center	1.25MW
3-2	〃	〃	2.5 MW
3-3	〃	〃	Stepped
5-1	W=2250,H=1000	Corner	1.25MW
5-2	〃	〃	2.5 MW
5-3	〃	〃	Stepped

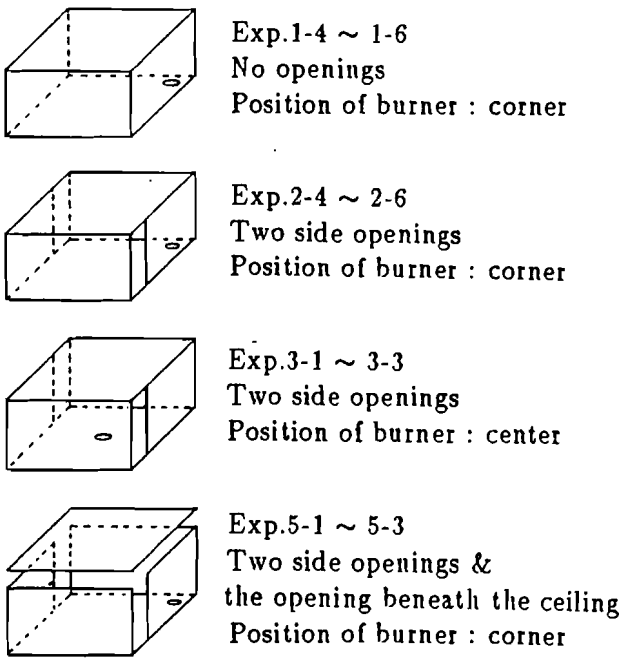

Fig.4 Schematics of Experimental conditions

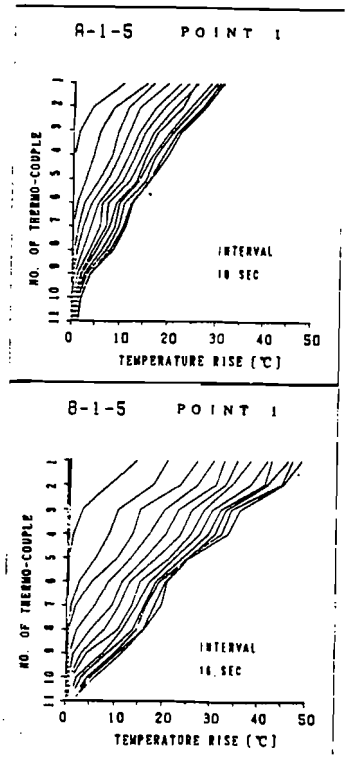

Fig.6-1 Vertical temperature profiles at 12 different time periods in Experiment 1-5

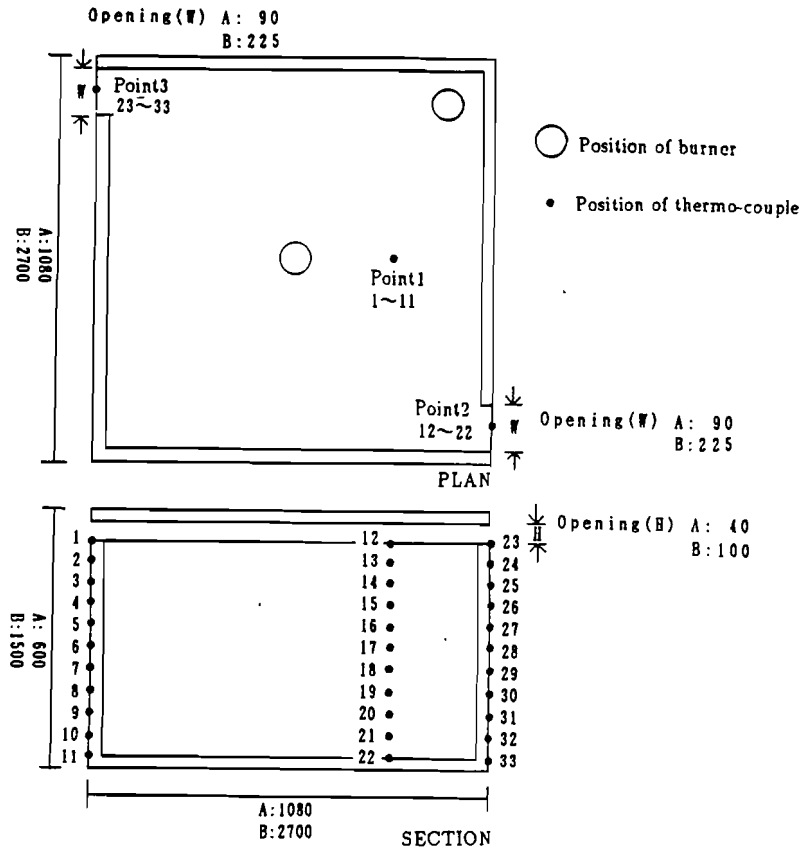

Fig.5 Plan and Section of Models (A:1/25, B:1/10)

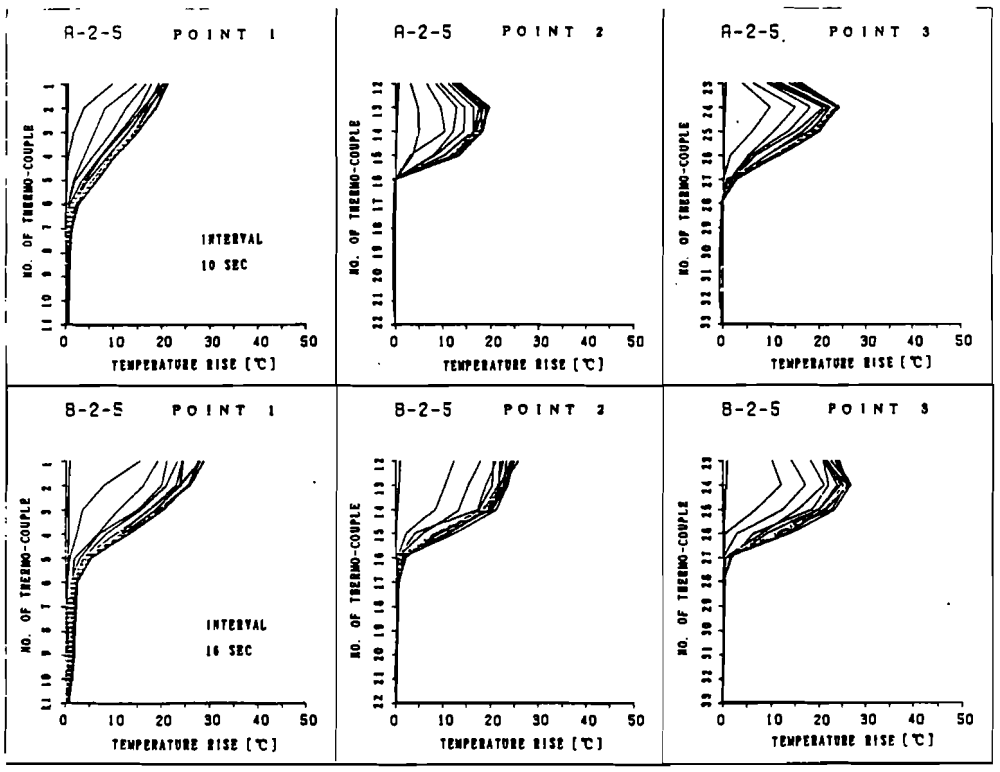

Fig.6-2 Vertical temperature profiles at 12 different time periods in Experiment 2-5

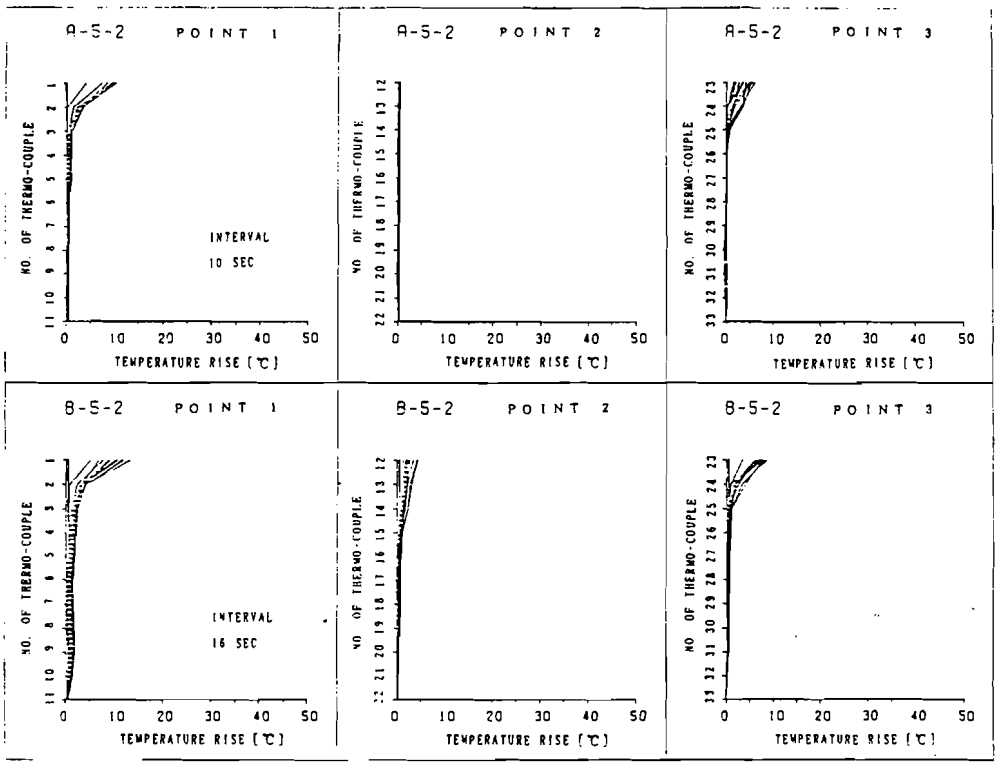

Fig.6-3 Vertical temperature profiles at 12 different time periods in Experiment 5-2

Experiment B-3-2 (Scale 1/10)

71"1 79"0 86"9 94"8

height of atrium space ; 1500mm
heat release rate ; 7.9kw
diameter of burner ; 150mm

(the only difference between Experiment B-2-5(Fig.7) and this is the position of the burner)

Fig.8 An example of fire whirl generated in Experiment B-3-2

Experiment A-2-5 (Scale 1/25)

5" 10" 15" 20" 25" 30"

height of atrium space ; 600mm
heat release rate ; 0.80kw
diameter of burner ; 60mm

Experiment B-2-5 (Scale 1/10)

7"9 15"8 23"7 31"6 39"5 47"4

height of atrium space ; 1500mm
heat release rate ; 7.9kw
diameter of burner : 150mm

Fig.7 Visualized smoke layer in 1/25 and 1/10 scale