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# EXPERIMENTAL STUDY ON SMOKE MOVEMENT WITH SCALE-MODEL

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## SUMMARY

The laws of scaling for unsteady-state smoke movement were 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 three stages, two different sizes (1:2.5), real fire test and its reduced model (1/40), and two different sizes (1:1.5) in wind tunnel considering wind effect. And the similarity in each stage was almost confirmed.

## 1. INTRODUCTION

One of the most important things for fire safety engineering is to predict smoke movement as a fire developing. Otherwise evacuation and extinguishing systems would not be planned adequately.

There are two methods to predict the smoke movement. The one is the method with reduced-scale experiments and the other is the numerical calculation method.

Both methods, however, have defects for analysis in unsteady states respectively. The weak point of the former is that it is impossible to fit all variables to the laws of scaling in experiments. In the latter there is uncertainty from giving exact boundary conditions, such as figure of fire flame and heat transfer from that, and the instability of calculation process.

This paper intends to show the way to predict the unsteady state smoke movement by a reduced scale experiment as similar as possible. The method is derived as follows.

1) The phenomenon that the temperature of the flame surface almost constant regardless of the size of heat source is adopted as the boundary condition for deriving the scaling law of heat convection.
2) Under the heat release rate which satisfies the scaling law derived in 1), the configuration of the flame becomes similar.
3) Simplifying the mechanism of surface heat transfer between smoke layer and (ceiling) wall, the scaling law for selecting wall material is derived. Adequacy of this law is tested by the results of experiments.

## 2. SCALING LAW

(1) Similarity of heat convection

The scaling law is drived from the $\pi$-parameters which are deduced by dimensional analysis of governing equations (continuity, conservation of momentum and conservation of energy). [1]

$$\left.\begin{aligned} \pi_1 &= \frac{L_0}{t_0 u_0} \\ \pi_2 &= \frac{\Delta p_0}{\rho u_0^2} \\ \pi_3 &= g\beta \frac{\Delta\theta_0 L_0}{u_0^2} \\ \pi_4 &= \frac{Q_0}{\rho c_p u_0 \Delta\theta_0 L_0^2} \end{aligned}\right\} \quad (1)$$

$L_0$: characteristic length
$u_0$: characteristic velocity
$t_0$: characteristic time
$Q_0$: characteristic heat release rate
$\Delta\theta_0$: characteristic temperature difference
$\Delta p_0$: characteristic pressure difference
$\beta$: coefficent of thermal expansion
$c_P$: specific heat under constant pressure
$\rho$: density

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 that the temperature difference between flame and its ambient is equal, $(\Delta\theta_M / \Delta\theta_R)$ becomes unit on the boundary. Consequently the scaling law is as follows;

$$\left.\begin{aligned} n(t) &= \left[\frac{Q_M}{Q_R}\right] = n(L)^{1/2} \\ n(Q) &= \left[\frac{t_M}{t_R}\right] = n(L)^{5/2} \\ n(u) &= \left[\frac{u_M}{u_R}\right] = n(L)^{1/2} \end{aligned}\right\} \quad (2)$$

subscripts $R$ and $M$ stand for real scale and model, respectively

(2) Similarity of flame

Configuration of fire flame is represented as Eq. (3) [2]

$$\left.\begin{aligned} \frac{L_f}{D} &= f\left(Q_f^*\right) \\ Q_f^* &= \frac{Q}{D^{5/2}} \end{aligned}\right\} \quad (3)$$

$L_f$, $D$: height and diameter of flame
$Q$: heat release rate

If $n(Q)=n(L)^{5/2}$ in Eq.(2) is satisfied, then

$$n(Q_f^*)=\frac{n(Q)}{n(D)^{5/2}}=\frac{n(L)^{5/2}}{n(D)^{5/2}} \qquad (4)$$

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

(3) Selection of material of wall

Heat flux from a smoke layer to the (ceiling) wall is governed by the heat transfer from the smoke layer to the surface of the wall and the heat conduction in the wall. Eq.(5) is derived under the assumption that

1) the surface temperature of the wall is equal to the temperature of the smoke layer,
2) the temperature gradient of smoke layer downstream mainly depends on the heat absorption into the (ceiling) wall, and
3) heat absorption into the wall is described approximately as that into semi-finite wall.

$$\dot{q}=\Delta\theta\sqrt{\frac{\lambda_w\rho_w c_w}{\pi t}}$$

$$n(\lambda_w\rho_w c_w)=n(L)^{3/2} \qquad (5)$$

$\lambda_w, \rho_w, c_w$; heat conductivity, density, specific heat of the wall, respectively

The vertical temperature profile of the smoke layer along the corridor becomes similar to the real scale experiment by replacing the material of wall of reduced scale model to that which satisfies the Eq.(5).[3]

## 3. COMPARISON OF SMOKE MOVEMENT BETWEEN SCALES

Experiments were conducted under the scaling laws described in 2. in three stages as follows;

1) the experiments using two types of reduced model (1/10 and 1/25) simulated smoke movement in atrium,
2) the 1/40 scale experiments simulated the real scale fire test in former KOKUGIKAN SUMO HALL (1984), and
3) the experiments in different size (1:1.5) in wind tunnel simulated the effect of wind to the smoke exhaust from the openings.

The similarity of temperature profile and smoke movement in each experiment is almost confirmed. Examples of the results are shown in Fig.1 and 2. Furthermore these results are

are visualized by video recording system and I prepared the picture to be able to compare the phenomena in two different scales by adjusting the time scale. This method is very powerful to understand the mechanism of smoke movement . Please request the video tape to the author.


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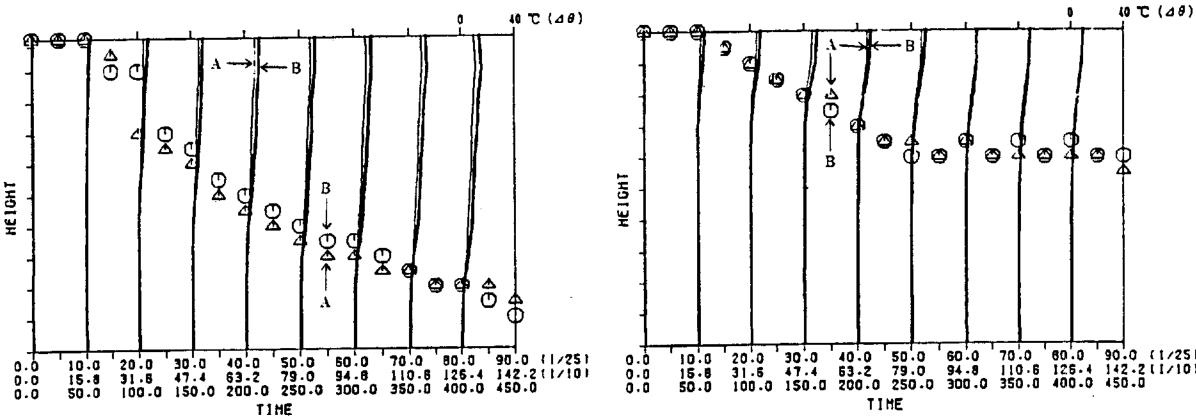


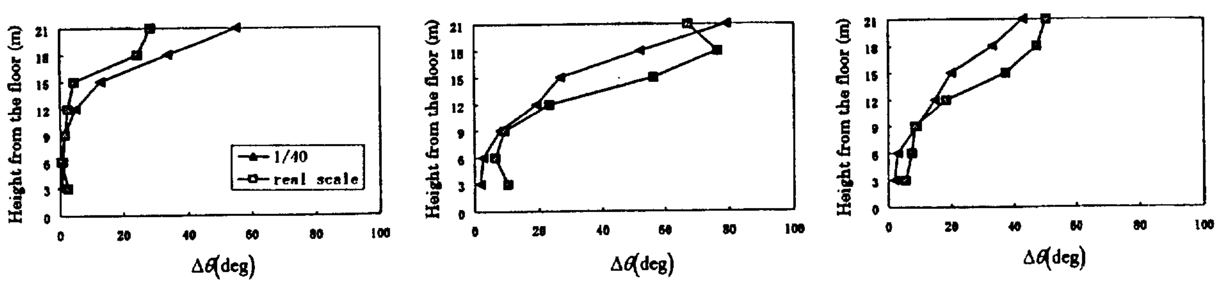

a)without opening (not air tight)

b)1/6 of the wall area is open

A:1/25, B:1/10 (real size of atrium is 27m×27m×15mh)

△◯:lower end of smoke layer identified by digital image processing techniques

Fig.1. Comparison of the vertical temperature profile and the smoke movement in reduced scale models




a)3min in real scale
28sec in 1/40

b)6min in real scale
57sec in 1/40

c)9min in real scale
85sec in 1/40

Fig.2. Comparison of the vertical temperature profile with time proceeding in Sumo Hall (82m×70m×24mh)

*Discussion*

Gerard Faeth: I'd be interested if you could tell me the way or the mechanism of making this smoke is these full-scale fires. I can imagine that if you tried that in the United States, you probably would be destroyed by the builder. What do you use for those simulations?

Makoto Tsujimoto: It's a railroad flare, used by the train conductor so that when the train runs into an accident or something, people will know that there's an accident.

Gunnar Heskestad: It seemed like most of the comparisons between full-scale and model were very good. And this is what we like to see. The frequencies and fluctuations seem to be right. Smoke descended about the correct rate. Was there anything during all of these experiments that suggested that the small-scale and large-scale fire might have some difference?

Makoto Tsujimoto: Yes. I think there is a difference in the radiation. For the first experiment, the scaled difference is 2.5. And the temperature is slightly higher in the larger scale. That's the only difference we know at this time.

Patrick Pagni: We are very interested in these excellent experiments. Japan has a long tradition of good computational models for smoke movement. Have you any plans to compare the computational results with your experimental results?

Makoto Tsujimoto: Well, actually, for the first experiment, we made computation using the Tanaka model and we obtained very good agreement.

James Quintiere: As many know, scale modeling is used in fields such as aircraft quite predominantly. To what extent is this kind of scale modeling used in Japan for building fire safety design?

Makoto Tsujimoto: This is used in very few cases.

James Quintiere: Too bad.