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SCALE MODELLING STUDIES OF SMOKE FILLING

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ABSTRACT

The transient development of the smoke layer due to a steady fire source in cubic atria was studied experimentally with a physical scale-down model. Scaling laws for scale modelling study were reviewed. Plume equation and correlation equation in literature for studying natural smoke filling with a steady fire were discussed. The clear height of the smoke layer was measured experimentally and correlated with the heat release rate of the fire and the time from the fire started in the atrium model base. The experimental results were compared with the measurements from a full-scale experiment through the preservation of the Froude number. The results were then applied to predict the time required to fill 80% of atrium height with smoke for cubic atria in the Hong Kong Special Administrative Region (HKSAR). Comparisons with those predicted by the plume equation and the correlation equation were made.

1. INTRODUCTION

An atrium is a space which resembles a courtyard passing through one or more structural floors with a ceiling that may not necessarily be glazed to the outside [1,2]. Many atrium buildings were built in the Hong Kong Special Administrative Region (HKSAR) in the past twenty years and large atria were found in shopping malls, hotels and office buildings [3]. From a survey of the geometrical shapes of 138 atria in the HKSAR, 108 atria (or 78% of them) were designed with open corridor at higher level [3], and 48 atria (or about 35% of them) can be classified as cubic with compartment volume varying from 400 to 26,000 m^3. Fire safety has become a concern of building designers and users because of the high occupant loading, large space volume, possibility of combustible items at the atrium base as activities, performances or exhibitions would be held regularly. The thermal aspect would not be critical that the heat release by burning materials in an atrium would be unable to heat up the large volume of air quickly to the flashover temperature [e.g. 4-6]. However, smoke is potentially lethal that would rapidly spread to other parts of the building, such as open corridor to the atrium at higher level. Smoke control is therefore important in the atrium building designs [1,7-10] and understanding the smoke movement and smoke filling process is essential.

Apart from the numerical simulations of the fire environment using computer models [e.g. 11,12], experimental studies on the smoke movement and smoke filling process in atria were reported in the literature [e.g. 13,14]. Time constant [5,6,15] accounting for building geometry and design fire characteristics would be a better parameter for specifying smoke filling in atria than the space volume used in the current fire code [8]. Studies on a full size building with hot smoke are good as the actual picture of the smoke filling process can be obtained [14,16,17]. However, it is very expensive and time-consuming to get a wide range of tests in full-size buildings. On-site measurement in an actual atrium would be constrained if using 'cold smoke'. Experimental studies with physical scale-down models are an alternative to the full-scale tests and have been used in studying smoke movement in indoor spaces [e.g. 13,18,19].

Experimental studies using physical scale-down models require the preservation of many parameters. Scaling laws with Froude number modelling technique are available in the literature for studying pre-flashover fires [20]. At the early stage of a fire, heat is mainly transferred from the burning object to the ceiling by convection. Buoyancy is the driving force for smoke movement in the natural ventilated space. Scaling laws were reviewed in this paper. The transient development of the smoke layer due to a steady fire in cubic atria was studied experimentally with a physical scale-down model and reporting the results becomes the objective of this paper. The experimental results were compared with the measurement from a full-scale experiment through the preservation of the Froude number. The time required to fill 80% of atrium height with smoke for cubic atria in the HKSAR was estimated. Comparisons with those predicted by the plume equation and the correlation equation in the literature were made.

2. SCALING LAWS

The governing differential conservation equations for mass, momentum and energy describing one-dimensional vertical fluid (in y-direction) are:

Mass

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho v)}{\partial y} = 0 \tag{1}$$

Momentum (Vertical)

$$\rho \frac{\partial v}{\partial t} + \rho v \frac{\partial v}{\partial y} = -\frac{\partial p'}{\partial y} + g(\rho_a - \rho) + \frac{4}{3}\mu \frac{\partial^2 v}{\partial y^2} \tag{2}$$

Energy

$$\rho c_p \left(\frac{\partial T}{\partial t} + v \frac{\partial T}{\partial y} \right) = k \frac{\partial^2 T}{\partial y^2} + \frac{\partial p}{\partial t} + Q \tag{3}$$

where

$$p' = p - p_a \tag{4}$$

$$\frac{dp_a}{dy} = -\rho_a g \tag{5}$$

Following the arguments by Quintiere [20], the above equations can be made dimensionless by introducing the normalizing parameters. They are the characteristic length L^*, the characteristic velocity v^*, the characteristic time t^* and the characteristic pressure p^*. With the initial ambient pressure p_0, density ρ_0 and temperature T_0, the normalized density $\hat{\rho}$, velocity $\hat{u}$, time $\hat{t}$ and length $\hat{y}$ are given by:

$$\hat{\rho} = \frac{\rho}{\rho_0} \tag{6}$$

$$\hat{v} = \frac{v}{v^*} \tag{7}$$

$$\hat{t} = \frac{t}{t^*} \tag{8}$$

$$\hat{y} = \frac{y}{L^*} \tag{9}$$

Taking

$$\rho_a = \rho_0 \tag{10}$$

$$p' = \hat{p}' p^* \tag{11}$$

$$p = \hat{p} p_0 \tag{12}$$

$$T = \hat{T} T_0 \tag{13}$$

The conservation equations (1) to (3) for mass, momentum and energy can be written as:

$$\pi_1 \frac{\partial \hat{\rho}}{\partial \hat{t}} + \frac{\partial(\hat{\rho}\hat{v})}{\partial \hat{y}} = 0 \tag{14}$$

$$\hat{\rho}\left(\pi_1 \frac{\partial \hat{v}}{\partial \hat{t}} + \hat{v} \frac{\partial \hat{v}}{\partial \hat{y}} \right) = -\pi_2 \frac{\partial \hat{p}'}{\partial \hat{y}} + \frac{4}{3}\pi_3 \frac{\partial^2 \hat{v}}{\partial \hat{y}^2} + \pi_4 (1 - \hat{\rho}) \tag{15}$$

$$\hat{\rho}\left(\pi_1 \frac{\partial \hat{T}}{\partial \hat{t}} + \hat{v} \frac{\partial \hat{T}}{\partial \hat{y}} \right) = \pi_3 \pi_5 \frac{\partial^2 \hat{T}}{\partial \hat{y}^2} + \pi_6 \frac{\partial \hat{p}}{\partial \hat{t}} + \hat{Q} \tag{16}$$

where

$$\pi_1 = \frac{L^*}{v^* t^*} \tag{17}$$

$$\pi_2 = \frac{p^*}{v^{*2} \rho_0} \tag{18}$$

$$\pi_3 = \frac{\mu}{v^* L^* \rho_0} = \frac{1}{Re} \tag{19}$$

$$\pi_4 = \frac{g L^*}{v^{*2}} = \frac{1}{Fr^2} \tag{20}$$

$$\pi_5 = \frac{k}{\mu c_p} = \frac{1}{Pr} \tag{21}$$

$$\pi_6 = \frac{L^* p^*}{\rho_0 v^* c_p T_0 t^*} = \frac{L^* \rho_0 v^{*2}}{\rho_0 v^* c_p T_0 \frac{L^*}{v^*}} = \frac{v^{*2}}{c_p T_0} \tag{22}$$

$$\hat{Q} = \frac{L^* Q}{\rho_0 v^* c_p T_0} \tag{23}$$

where Re, Fr and Pr are the Reynolds number, Froude number and the Prandtl number respectively.

Taking

$$t^* = \frac{L^*}{v^*} \quad (24)$$

$$p^* = \rho_0 v^{*2} \quad (25)$$

$$\pi_1 = \pi_2 = 1 \quad (26)$$

The experiments would be performed in air at normal ambient conditions for convenience with π_4 the primary group preserved. For natural convection, π_4 is set equal to 1. The solid boundary effects are assumed nonexistent or unimportant for an atrium having a large volume, π_3 (or Reynolds number) therefore would be ignored in the Froude number modelling. The concerned region is far away from the combustion region. A point source representation would be used with the chemical energy production rate Q. By Bousinnesq assumption:

$$1 - \hat{\rho} = \hat{T} - 1 \quad (27)$$

A normalized temperature is derived by Quintiere [20]:

$$\pi_4(1-\hat{\rho}) = (\pi_4 \zeta)\left(\frac{\hat{T}-1}{\zeta}\right) = \left(\frac{\hat{T}-1}{\zeta}\right) \quad (28)$$

Hence,

$$\pi_4 \zeta = 1 \quad (29)$$

$$\zeta = \frac{v^{*2}}{gL^*} \quad (30)$$

Let

$$\frac{\hat{Q}}{\zeta} = 1 \quad (31)$$

with equation (23), equation (31) can be written as:

$$\frac{\hat{Q}}{\zeta} = \frac{L^*\left(\frac{Q}{L^{*3}}\right)}{\rho_0 v^* c_p T_0} \frac{gL^*}{v^{*2}} = 1 \quad (32)$$

$$v^* = \left(\sqrt[3]{\frac{g}{\rho_0 c_p T_0}}\right)\left(\frac{Q}{L^*}\right)^{\frac{1}{3}} \quad (33)$$

For scaling studies with preservation of the Froude number of the scale model and the real size atrium (denoted with subscript M and R respectively),

$$\pi_4\big|_M = \pi_4\big|_R \quad (34)$$

$$\frac{gL_M^*}{v_M^{*\,2}} = \frac{gL_R^*}{v_R^{*\,2}} \quad (35)$$

The scaling law for the velocity and length of the scale model and real size atrium is:

$$\left(\frac{L_M^*}{L_R^*}\right)^{\frac{1}{2}} = \frac{v_M^*}{v_R^*} \quad (36)$$

Time in the scale model and the real size atrium can be related by:

$$t_R^* = \frac{L_R^*}{v_R^*} \quad (37)$$

$$t_M^* = \frac{L_M^*}{v_M^*} \quad (38)$$

The scaling law for the time and length of the scale model and real size atrium can be written as:

$$\frac{t_M^*}{t_R^*} = \frac{\frac{L_M^*}{v_M^*}}{\frac{L_R^*}{v_R^*}} = \frac{L_M^*}{L_R^*}\frac{v_R^*}{v_M^*} = \frac{L_M^*}{L_R^*}\left(\frac{L_M^*}{L_R^*}\right)^{-\frac{1}{2}} \quad (39)$$

$$\frac{t_M^*}{t_R^*} = \left(\frac{L_M^*}{L_R^*}\right)^{\frac{1}{2}} \quad (40)$$

Assume g, ρ_0, c_p, T_0 are constant for the scale model studies, equation (33) can be written as:

$$v^* = \text{constant} \times \left(\frac{Q}{L^*}\right)^{\frac{1}{3}} \quad (41)$$

$$\frac{v_M^*}{v_R^*} = \left(\frac{Q_M}{L_M^*}\right)^{\frac{1}{3}}\left(\frac{L_R^*}{Q_R}\right)^{\frac{1}{3}} \quad (42)$$

$$\left(\frac{L_M^*}{L_R^*}\right)^{\frac{1}{2}} = \left(\frac{Q_M}{L_M^*}\right)^{\frac{1}{3}}\left(\frac{L_R^*}{Q_R}\right)^{\frac{1}{3}} \quad (43)$$

The scaling law for the heat release rate and length of the scale model and real size atrium can be written as:

$$\frac{Q_M}{Q_R} = \left(\frac{L_M^*}{L_R^*} \right)^{\frac{5}{2}} \quad (44)$$

The equations (36), (40) and (44) are scaling laws with preservation of the Froude number used in this study.

3. SMOKE CLEAR HEIGHT

Without a smoke extraction system in an atrium, the smoke layer thickness increases and the clear height decreases with a fire at the atrium base. The natural filling of smoke in the atrium of floor area A (m^2) and height H (m) without an opening in the upper layer by considering only the mass transfer is given by Chow [5]:

$$\frac{d}{dt}[\rho A(H - y)] = m_p \quad (45)$$

where t (s) is time from the fire started, ρ (kgm^{-3}) is air density and y (m) is the smoke clear height.

The amount of smoke produced from the burning materials is not very large but the upward-moving fire plume will entrain air to give a large volume of smoke in a real atrium fire. The entrainment rate is usually taken to be the smoke production rate m_p (kgs^{-1}) [5,6,9,21,22].

The mass flow for an axisymmetric plume by entrainment m_p (kgs^{-1}) at height of smoke layer y (m) from a point fire source with heat release rate of Q (kW) on the floor away from walls is given by [21,22]:

$$m_p = 0.071\ Q^{\frac{1}{3}}\ y^{\frac{5}{3}} \quad (46)$$

Following the derivation by Chow [5], substitute equation (46) into equation (45):

$$\frac{d}{dt}[\rho A(H - y)] = 0.071\ Q^{\frac{1}{3}} y^{\frac{5}{3}} \quad (47)$$

Neglecting dρ/dt for simplification but this must be considered carefully,

$$\frac{d}{dt} y = -\frac{0.071\ Q^{\frac{1}{3}} \cdot y^{\frac{5}{3}}}{\rho \cdot A} \quad (48)$$

The smoke layer can be visualised by solving the clear height y (m) in terms of time t (s):

$$\int_H^y y^{-\frac{5}{3}} dy = -\frac{0.071\ Q^{\frac{1}{3}}}{\rho \cdot A} \int_0^t dt \quad (49)$$

And the location of the smoke layer interface f is given by:

$$f = \frac{y}{H} = \left(C_1 Q^{C_2} t^{C_3} + C_4 \right)^{C_5} \quad (50)$$

Taking air density ρ of 1.2 kgm^{-3} for a cubic atrium, the constants in the above equation are:

$$C_1 = \frac{2}{3} \frac{0.071}{\rho} \frac{H^{\frac{2}{3}}}{A} = 0.0018 \quad (51)$$

$$C_2 = \frac{1}{3} \quad (52)$$

$$C_3 = C_4 = 1 \quad (53)$$

$$C_5 = -\frac{3}{2} \quad (54)$$

An empirical equation of the smoke layer development in a space due to a steady fire with heat release rate of Q (kW) appeared in NFPA 92B [7] and described by Klote [10] is given by:

$$f = \frac{y}{H} = 1.11 - 0.28 \ln \left(\frac{t Q^{\frac{1}{3}} H^{-\frac{4}{3}}}{\frac{A}{H^2}} \right) \quad (55)$$

Equation (55) holds for the geometrical aspect factor $\frac{A}{H^2}$ between 0.9 and 14 and for clear height f ≥ 0.2 (i.e. 20% of the ceiling height). The geometrical aspect factor of the cubic atrium model referred in this study is equal to 1.

4. EXPERIMENTAL SET-UP

A clear plastic (acrylic) model of size 0.5 m × 0.5 m × 0.5 m was constructed to study the smoke filling process in cubic atria. Homogeneous smoke gas in the model and constant outside ambient temperature were assumed. The junctions of the model were sealed with adhesives. Two make-up air inlets of size 0.15 m × 0.1 m (H) were constructed at the low level as shown in Fig. 1. The model was cleaned for each test. A point fire heat source was placed at the middle of the model base. The fire was controlled by regulating town gas supply flow rate through a supply nozzle. 100% combustion efficiency was assumed in calculating the heat release rate. Because burning the fuel gas would give a clean fire, a smoke pellet (Smoke Products Ltd., Northants, UK) of weight 3.5 g is placed over it to generate visible smoke. Tungsten lamps were used for illuminating the model and the optical system arrangement is shown in Fig. 1.

The experiments were conducted under normal atmospheric pressure. Five heat release rates Q_M of 0.98, 1.07, 1.50, 2.20 and 3.41 kW were considered. Experiment for each condition was repeated and a total of 20 tests were conducted.

The smoke filling process was continuously recorded by a video camera from views X and Y as shown in Fig. 1. The images of the process (from views X and Y) were also taken by a 35 mm camera with a 50 mm lens installed. The aperture and shutter speed were set at *f*/2.8 and 1/125 s (+0, −0.45 ms) with the shooting frequency of 1 s (± 0.05 s) or 0.5 s (± 0.05 s). The images were recorded on 35 mm × 24 mm films of speed ISO400 with resolving power 125 $ll\cdot mm^{-1}$ for contrast 1:1000 and 40 $ll\cdot mm^{-1}$ for contrast 1.6:1.

5. RESULT AND DISCUSSION

Quality images were recorded for the experiments and a 2-layer structure (smoke and smoke clear layers) in the model was observed. A typical photograph of the smoke filling process is shown in Fig. 2. Transient values of the clear height (expressed as a fraction of ceiling height) f_M were determined by measuring the images captured by both camera and video camera. It was found that the f_M recorded by the camera and the video camera agreed with each other as shown in Fig. 3 with dashed lines showing ± 10% error. The average measured values of all observations were used for further analysis.

An axisymmetric smoke plume was observed in the experiments. The natural smoke filling process would be described by equation (50) and the constants would be determined experimentally. The measured transient clear height for the atrium model for the 5 heat release rates of 0.98, 1.07, 1.50, 2.20 and 3.41 kW was indicated with o, ◊,□ , Δ and ∇ as shown in Fig. 4. The constants were determined by least square fit with the measured clear height as a percentage of ceiling height of the model f_M, heat release rate Q_M (kW) and time t_M (s).

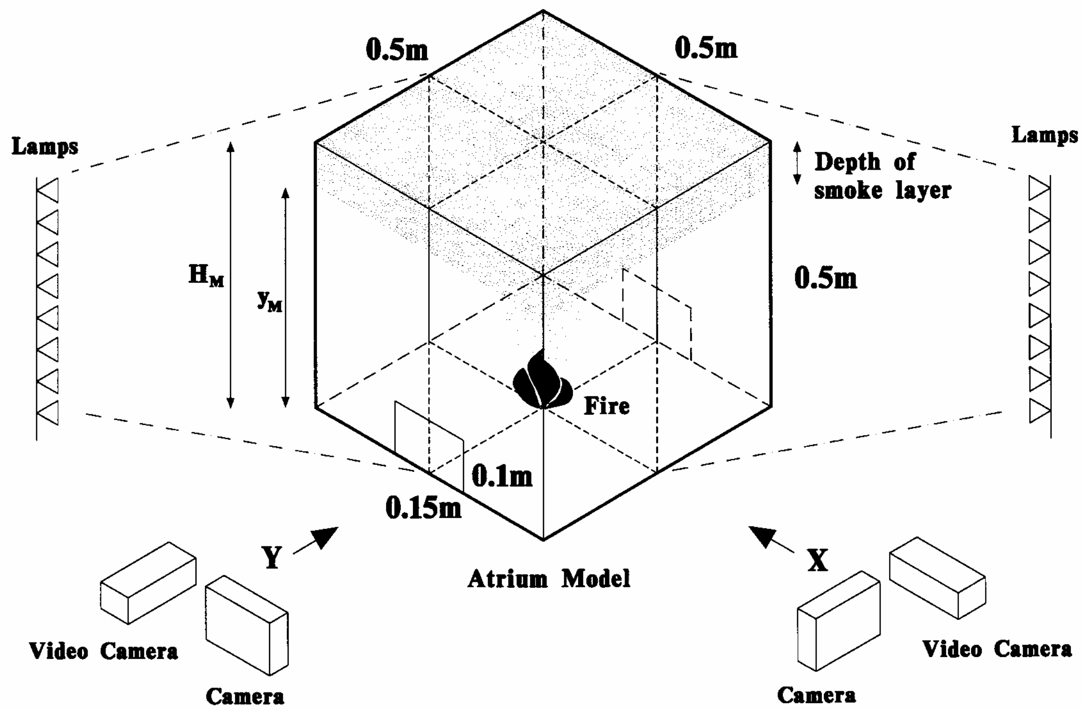

Fig. 1: Experimental setup

A correlation equation was found:

$$f_M = \left(1.07 + 1.23\times10^{-6} Q_M^{5.97} t_M^{12.4}\right)^{-0.1} \quad (56)$$

where,

$$0.2 \le f_M \le 1 \quad (57)$$

with a Pearson's product-moment correlation coefficient [23] of 0.973.

The values of f_M predicted by the correlation equation are plotted in Fig. 4 as well. The empirical equation holds for Q_M up to 3.41 kW.

Fig. 2: Typical photograph of the smoke filling process

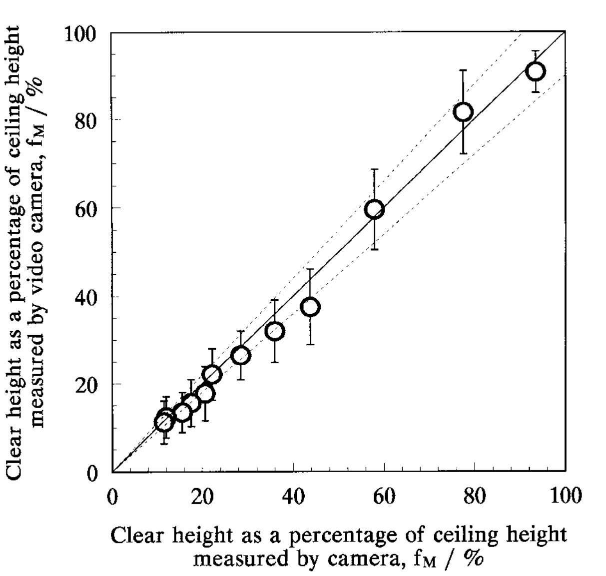

Fig. 3: Clear height as a percentage measured by camera and video camera

Full-scale experiments on smoke control in a large space were carried out by Yamana and Tanaka [4] in an atrium of size 30 m × 24 m × 26.3 m (H) at the Building Research Institute (BRI, Ministry of Construction, Japan). The geometry is very similar to a cubic atrium referred in this study and the geometrical aspect factor $\frac{A}{H^2}$ is 1.04. A methanol fire of size 1.8 m × 1.8 m, thermal power of 1300 kW with smoke candles for generating visible smoke was used. The transient smoke layer thickness was measured by visual inspection, photometers and thermocouples. The natural smoke filling experiments referred in the study by Yamana and Tanaka [4] are very suitable for comparison with the present study since no windows were open.

The transient variation of clear height in the BRI atrium was predicted by correlating the time scale on the model through the preservation of the Froude number. The scaling effects of physical length L (m), heat release rate Q (kW) and time t (s) related by the scaling factor $\left(\frac{L_M}{L_R}\right)$ would be determined by equations (40) and (44). The subscripts M and R denote parameters for the scale-down model and the full-size atrium respectively.

The volume of the BRI atrium V_R (m^3) is 18,936 m^3 and the characteristic length L_R (m) of the BRI atrium is 26.3 m calculated by:

$$L_R = V_R^{\frac{1}{3}} \quad (58)$$

A scaling factor $\left(\frac{L_M}{L_R}\right)$ of 1/53.3 was applied and the predicted clear height calculated by the correlation equation (56) with Q_M = 0.0627 kW corresponding to Q_R = 1300 kW fire size in the BRI atrium was used. The model time t_M (s) is related to the real time of the atrium t_R (s) by equation (40) that:

$$t_R = 7.3\, t_M \quad (59)$$

The variation of f_R for natural smoke filling experiment is plotted in Fig. 5, together with the measured data by Yamana and Tanaka [4]. The result predicted by Yamana and Tanaka [4] is shown for comparison. The predicted results agree with the observations by Yamana and Tanaka [4]. Both showed a slower filling rate at the early stage of the experiment. The predictions made by equations (50) to (55) were shown for comparison.

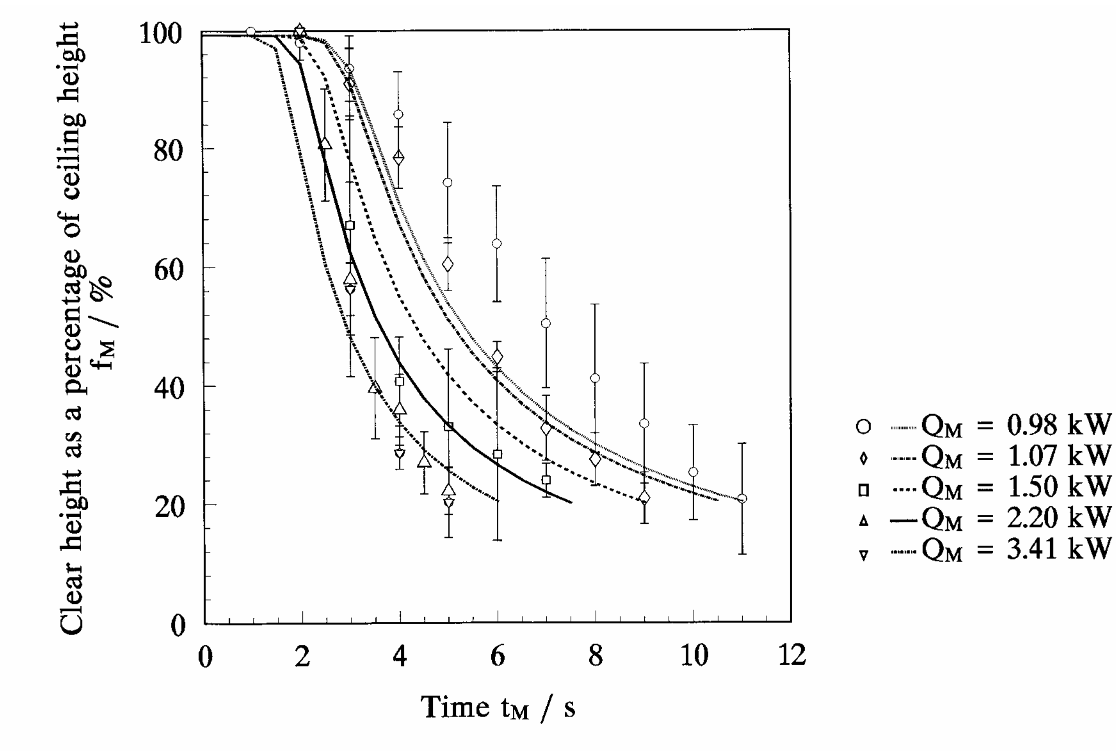

Fig. 4: Variation of clear height for the atrium model

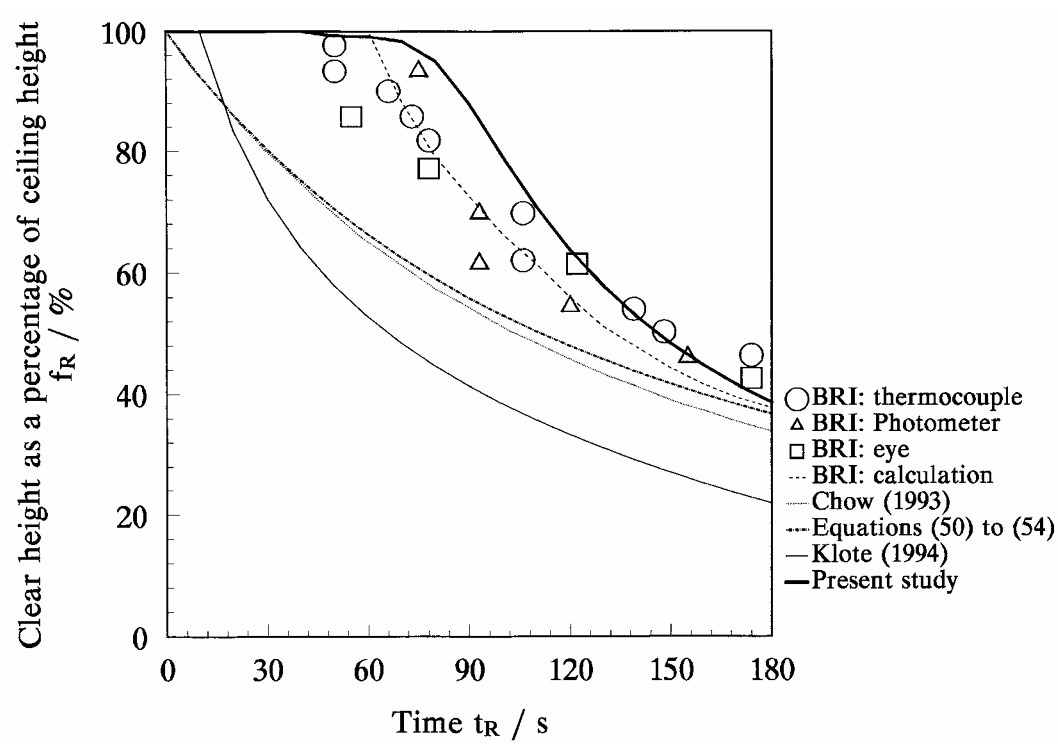

Fig. 5: Variation of clear height for the BRI atrium (natural filling experiment)

6. TIME REQUIRED TO FILL 80% OF ATRIUM HEIGHT WITH SMOKE

The whole atrium may not be completely filled with smoke and reference time required to fill 80% of atrium height was recommended to specify the smoke filling process in the space by Chow [5,6] and Chow and Li [15]. The time required to fill 80% of atrium height t_{80} (s) would indicate the time taken to fill the open corridor at upper levels of the atrium with smoke. If the safe egress time for the atrium with open corridor is taken to be 150 s (2.5 min) [8], the smoke filling time t_{80} (s) would be longer than this.

Since the $f_M \geq 20\%$ was measured in present study, the experimental results were applied to estimate the smoke filling time t_{80} (s) for cubic atria in the HKSAR. The t_{80} (s) calculated from equation (56) by setting $f_M = 20\%$ and correlating the time scale and the heat release rate by equations (40) and (44) is shown in Fig. 6 for atrium volume varying from 2,500 to 40,000 m^3 with a fire size of 2.5 and 5 MW at the atrium base. The design fire size of an atrium depends on fire load and would be affected by the use of the atrium. The t_{80} (s) predicted by the smoke filling equations (50) to (55) was plotted in the figure for comparison. The t_{80} (s) predicted by time constant using plume expression [e.g. 5] is shown in the figure. The calculated t_{80} (s) of the present study fell in the range of the predictions made from the smoke filling equations. However, the longer smoke filling time t_{80} (s) was predicted by equation (50), with constants in equations (51) to (54) and by using the time constant [e.g. 5], both were derived from the natural smoke filling equation for considering mass transfer only. The local fire regulation [8] specified that smoke extraction systems are required if atrium volume exceeds 28,000 m^3 (or if the basement volume exceeds 7,000 m^3). Of a design fire 5 MW, t_{80} (s) for a cubic atrium estimated by present study is 200 s as shown in Fig. 6. The estimations made by equation (50) with constants in equation (51) to (54), by Chow [5] and by Klote [10] are 271, 220 and 143 s respectively.

7. CONCLUSIONS

The transient development of the smoke layer due to a steady fire source in cubic atria was studied experimentally with a physical scale-down model. Correlation equation for clear height of the smoke layer was determined. The experimental results were compared with the measurements from a full-scale experiment through the preservation of the Froude number. Good agreement with the observations by Yamana and Tanaka [4] was found.

The experimental results from this study were used to predict the time required to fill 80% of atrium height with smoke for cubic atria in the HKSAR through the preservation of the Froude number. Comparisons with those predicted by the plume equation [21], by time constant [e.g. 5] and the correlation equation [10] were made. Shorter smoke filling time t_{80} (s) was estimated in comparison with those predictions by considering mass transfer only. The predicted smoke filling time was found to be longer than those predicted by the correlation equation by Klote [10].

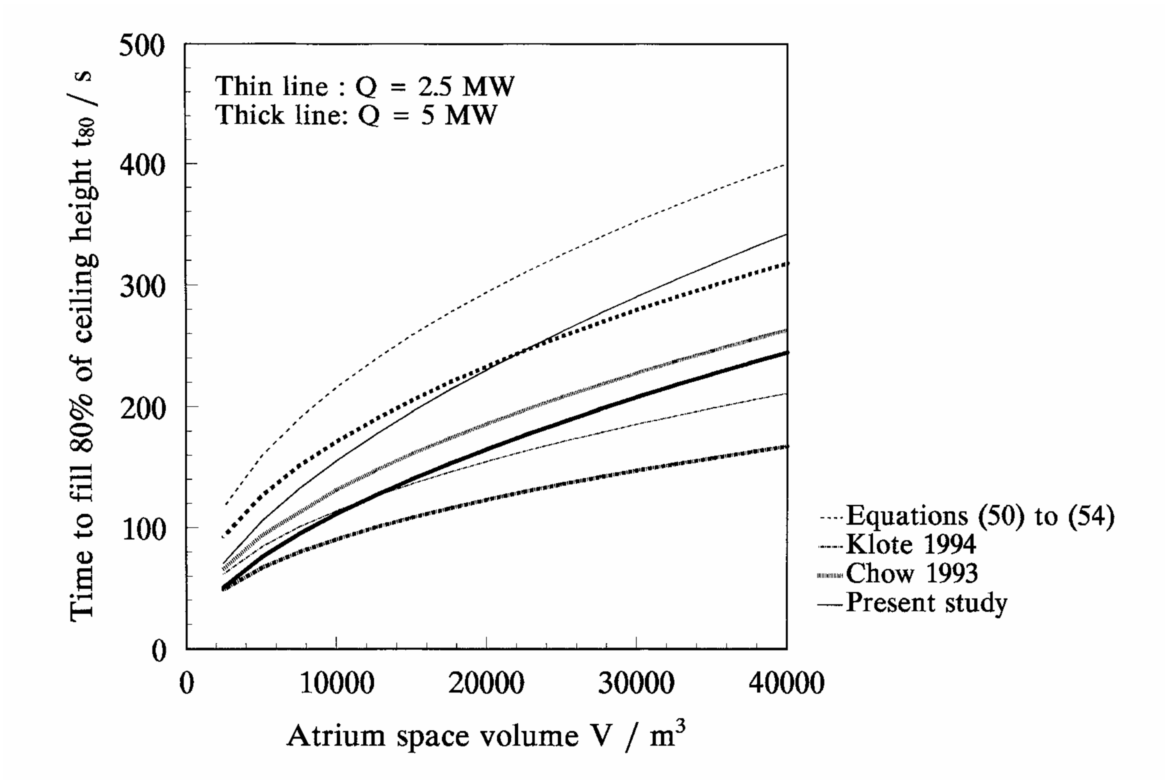

Fig. 6: Time required to fill the smoke layer thickness equal to 80% of the ceiling height

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NOMENCLATURE

A	area, m^2
C	constant
c	specific thermal capacity, $kJkg^{-1}K^{-1}$
f	clear height y as a percentage of ceiling height H, %
g	gravity, ms^{-2}
H	ceiling height, m
k	thermal conductivity, $kJs^{-1}m^{-1}K^{-1}$
L	length, m
m	smoke production rate, kgs^{-1}
p	pressure, Pa
Q	chemical energy production rate, kW
T	Temperature, K
t	time, s
V	volume, m^3
v	velocity, ms^{-1}
y	smoke clear height, m
μ	viscosity, $kgm^{-1}s^{-1}$
π	dimensional group
ρ	air density, kgm^{-3}
ζ	parameter defined in equation (30)

Subscripts

0	initial condition
1,2..	conditions 1,2…
80	of 80% ceiling height
a	of ambient air
M	of scale model
p	of plume
R	of full size atrium

Superscripts

*	characteristic quantity
^	normalized quantity

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