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ON THE EQUATIONS FOR FLASHOVER FIRE IN SMALL COMPARTMENTS

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ABSTRACT

Equations for studying flashover fire were studied experimentally in this paper. Experiments were carried out in a chamber inside a full-scale burning test hall of the joint project between The Hong Kong Polytechnic University and the University of Science and Technology of China. Three correlation equations on estimating the critical heat release rates for flashover were considered. The two-layer zone model CFAST on predicting flashover was also studied. Results are useful in understanding the possibility of flashover in small shops such as those of a cabin design, while carrying out hazard assessment with fire safety engineering.

1. INTRODUCTION

It is essential to estimate the probable fire environment in a compartment while using engineering performance-based fire codes [e.g. 1,2] for providing appropriate fire safety. Of which, the flashover phenomenon is of great interest and the Authority should have a clear understanding on that for approving fire safety design. Literature included the thermal flashover in a compartmental fire analyzed by Thomas et al. [3] based on explosion theory. For the rate of heat gained of the smoke layer higher than the rate of heat lost, it is possible to bring about flashover. Single zone model was analyzed by Babrauskas [4], and Quintiere and McCaffrey [5]; and with Computational Fluid Dynamics (CFD) by Lockwood and Malalasekera [6]. Analysis of non-linear phenomenon on heat release equation was reported by Bishop et al. [7] and Graham et al. [8].

On the other hand, fire models are commonly used in hazard assessment. There are different views [e.g. 9] on how good the equations available for estimating the fire environment and fire models can predict. Although there are many experimental data available in the literature on assessing or justifying the models, systematic studies on experimental fires in this part of the world are absent. Carrying out full-scale burning tests would be good in providing those information, and assessing the available equations and models for estimating the fire environment such as smoke temperature.

In view of that, an experimental burning hall [10] was built as a joint project between the University of Science and Technology of China (USTC) and The Hong Kong Polytechnic University (PolyU). A series of full-scale burning tests on flashover fires were performed. Results are useful for understanding the possibility of flashover in small retail shops, including the cabin design [11] which is commonly used in airport terminals and railway stations. The fire environment in the small shops must be clearly understood before putting in appropriate fire services installation.

2. TWO-LAYER ZONE MODEL

A two-layer zone model [e.g. 12] as shown in Fig. 1 is commonly used in fire hazard assessment. Conservation of enthalpy gives the rate of enthalpy increase of smoke layer $\dot{E}_s$ as:

$$\dot{E}_s = C_p m_s \frac{dT_s}{dt} \tag{1}$$

where C_p is the specific heat capacity of smoke, m_s is the mass of smoke layer and T_s is the smoke layer temperature. $\dot{E}_s$ can be expressed in terms of the enthalpy gain $\dot{E}_g$ and enthalpy lost $\dot{E}_\ell$ as:

$$\dot{E}_s = \dot{E}_g - \dot{E}_\ell \tag{2}$$

where $\dot{E}_g$ comes from the enthalpy influx rate of the plume $\dot{E}_p$; and $\dot{E}_\ell$ is expressed in terms of the enthalpy lost through the wall $\dot{E}_c$, ceiling jet $\dot{E}_o$ and radiation $\dot{E}_{sr}$:

$$\dot{E}_\ell = \dot{E}_o + \dot{E}_c + \dot{E}_{sr}$$

with $\dot{E}_o$, $\dot{E}_c$ and $\dot{E}_{sr}$ expressed in terms of the mass of gas $\dot{m}_g$, surface area A_u and A_ℓ of the upper and lower layers, wall temperature T_w, emissivity of smoke ε, and Stefan-Boltzman constant σ of value 5.669 × 10^{-8} $Wm^{-2}K^{-4}$.

$$\dot{E}_o = \dot{m}_g C_p T_s \quad (3)$$

$$\dot{E}_c = A_u h_c (T_s - T_w) \quad (4)$$

$$\dot{E}_{sr} = \varepsilon\sigma(A_u + A_\ell)(T_s{}^4 - T_w{}^4) \quad (5)$$

Mass conservation on the entire system gives the mass rate of smoke flowing out of the upper part of the vent $\dot{m}_g$ in terms of the air intake rate $\dot{m}_a$ at the lower part of the vent and pyrolyzed rate of the fuel $\dot{m}_f$:

$$\dot{m}_g = \dot{m}_a + \dot{m}_f \quad (6)$$

There should be sufficient air for combustion before flashover and so the fire is fuel-controlled. $\dot{E}_p$ can be expressed in terms of the combustion efficiency η, calorific value of the fuel ΔH_c, and convective fraction of heat release rate to the plume λ_c as:

$$\dot{E}_p = \lambda_c \eta \dot{m}_f \Delta H_c \quad (7)$$

For liquid fuel as used in this experimental study, pyrolyzed rate $\dot{m}_f$ is expressed in terms of the calorific value of the fuel ΔH_f, pool fire area A_f and total radiative heat flux of the flame $\dot{q}''_{tot}$ as:

$$\dot{m}_f = \frac{A_f}{\Delta H_f} \dot{q}''_{tot} \quad (8)$$

where $\dot{q}''_{tot}$ is expressed in terms of the radiative heat flux of the wall $\dot{q}''_{wr}$, the re-radiated heat flux of the flame $\dot{q}''_{rr}$, the radiative heat flux from the flame $\dot{q}''_{pr}$ and the thermal radiation flux from the smoke $\dot{q}''_{sr}$.

$$\dot{q}''_{tot} = \dot{q}''_{pr} + \dot{q}''_{wr} + \dot{q}''_{sr} - \dot{q}''_{rr} \quad (9)$$

In this paper, $\dot{q}''_{wr}$ and $\dot{q}''_{rr}$ are relatively smaller than $\dot{q}''_{pr}$ and $\dot{q}''_{sr}$, and so being neglected in the calculation.

Flashover may occur if $\dot{E}_g$ is greater than $\dot{E}_\ell$. Once flashover occurs, the fire is changed from fuel-controlled to ventilation-controlled. Under this situation, $\dot{E}_p$ cannot be calculated by equation (7).

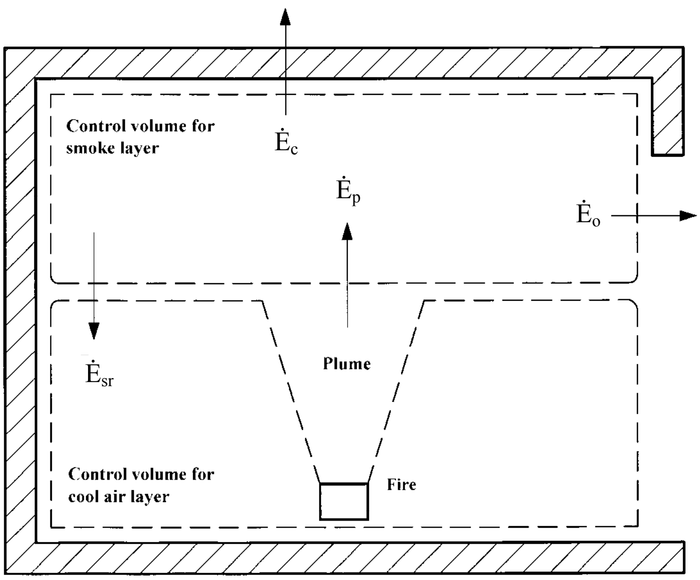


Fig. 1: Two-layer zone model

The effects of ventilation on developing of a compartment fire were studied by Kawagoe [13]. With large volume of experimental data, $\dot{m}_f$ was found to be related to the ventilation factor $A_v\sqrt{H_v}$, where A_v and H_v are the area and height of a vertical opening of the fire room. This was simplified further by Babraukas [4]. Further analysis carried out by Thomas et al. [3,14] and Quintiere et al. [15,16] led to several correlation equations. Note that the rates of air intake and smoke flowing out would be changed before and after flashover. For a pre-flashover fire, $\dot{m}_g$ was found by Quintiere [16]:

$$\dot{m}_g = \frac{2}{3} C_1 \rho_o A_v H_v^{1/2} \sqrt{2g\left(\frac{T_o}{T}\right)\left(1-\frac{T_o}{T}\right)} \qquad (10)$$

where C_1 is a flow coefficient found to be about 0.7 by Bishop et al. [7], g is the acceleration due to gravity of 9.8 ms^{-2}, T_o is the initial air temperature of the compartment (taken as 300 K) and T is the average temperature of the smoke layer.

Ideal gas law gives the air density ρ at T as:

$$\rho = \frac{P}{RT} \qquad (11)$$

P can be taken as the atmospheric pressure of 101,325 Pa and R is the ideal gas constant of 287 $Jkg^{-1}K^{-1}$.

In view of equation (10), $\dot{m}_g$ depends not only on the ventilation condition, but also on the smoke temperature.

For a post-flashover fire, $\dot{m}_a$ depends on the ventilation factor as:

$$\dot{m}_a = C_2 A_v H_v^{1/2} \qquad (12)$$

where C_2 is the proportionality constant of values lying between 0.4 to 0.61 $kgs^{-1}m^{-5/2}$.

$\dot{m}_f$ also depends on the ventilation factor as:

$$\dot{m}_f = C_3 A_v H_v^{1/2} \qquad (13)$$

where C_3 is about 0.09 $kgs^{-1}m^{-5/2}$.

Putting equations (12) and (13) into equation (6):

$$\dot{m}_g = C_4 A_v H_v^{1/2} \qquad (14)$$

where C_4 is of value about 0.6 $kgs^{-1}m^{-5/2}$.

3. PREDICTION OF CRITICAL HEAT RELEASE RATES FOR FLASHOVER

There are many equations developed for predicting the critical heat release rates for flashover. In fact, systematic estimation on the smoke temperature was reported by Walton and Thomas [17]. The three equations listed below are commonly used:

- Babrauskas Equation [4]

  Taking the smoke temperature rise of 575°C (with ambient temperature of 20°C) as flashover, the critical heat release rate for flashover $\dot{Q}_f$ (in kW) is:

  $$\dot{Q}_f = 750 A_v \sqrt{H_v}$$

  Comparing with experimental results, two-thirds of the data of $\dot{Q}_f$ were lying between $450A_v\sqrt{H_v}$ to $1050A_v\sqrt{H_v}$.

- McCaffrey, Quintiere and Harkeleroad (MQH) Equation [15]

  Upper layer temperature rise ΔT was fitted by over 100 sets of experimental data:

  $$\Delta T = 480\left[\frac{\dot{Q}}{\sqrt{g}C_p\rho_o T_o A_v\sqrt{H_v}}\right]^{2/3}\left[\frac{h_k A_T}{\sqrt{g}C_p\rho_o A_v\sqrt{H_v}}\right]^{-1/3} \qquad (16)$$

  Taking ΔT of 575°C as the criterion for flashover, and putting in numerical values of C_p, ρ_o and T_o, $\dot{Q}_f$ is expressed in terms of the available heat transfer area of the room A_T and the heat transfer coefficient h_k:

  $$\dot{Q}_f = 740\left(h_k A_T A_v\sqrt{H_v}\right)^{1/2} \qquad (17)$$

- Thomas Equation [14]

  Heat balancing of the smoke layer with simplification gives two terms on heat lost $\dot{Q}_\ell$ and $m_g C_p(T - T_o)$, $\dot{Q}_f$ is given by:

  $$\dot{Q}_f = m_g C_p (T - T_o) + \dot{Q}_\ell \qquad (18)$$

  Data analysis gives:

  $$\dot{Q}_f = 378 A_v\sqrt{H_v} + 7.8 A_T \qquad (19)$$

4. EXPERIMENTAL STUDIES

A chamber of length 4 m, width 3 m and height 3 m constructed with double layers of fire-rated gypsum board of 7 mm thick was used for the experimental study. A door of width 1.6 m and height 2.2 m was constructed as shown in Fig. 2. It was placed in the PolyU/USTC burning hall [10] of length 24 m, width 18 m and height 30 m. Diesel pool fires of three different sizes were tested:

- S1: Square tray of size 1 m by 1 m
- S2: Square tray of size 0.5 m by 0.5 m
- C2: Circular pan of diameter 0.975 m

The fuel was put above a weighing device for measuring its transient mass during the burning process.

Three thermocouple trees A, B and C were placed inside the chamber for measuring the smoke temperature. Thermocouple trees A and B were placed close to the wall. There were five thermocouples placed at 5 cm, 40 cm, 80 cm, 120 cm and 165 cm vertically below the ceiling. Thermocouple tree C had 10 thermocouples arranged in a T-shape, with five thermocouples placed horizontally at the same height with a separation distance of 40 cm from each other. Another five thermocouples were placed vertically with distribution the same as thermocouple trees A and B.

All data from the weighing device and thermocouples were transmitted to a personal computer for processing. A metre stick was used to measure the smoke layer interface with suitable arrangement of illumination.

Heat release rate $\dot{Q}$ of the fire was estimated by the burning area A_b with heat release rate per area $\dot{Q}_o$ taken as 1986 kWm^{-2}:

$$\dot{Q} = \alpha A_b \dot{Q}_o \tag{20}$$

where α is the factor on combustion efficiency, taken as 0.7 in this paper.

From the changes of the heat release rate curve, $\dot{Q}$ is estimated from the mass loss rate $\dot{M}_{dis}$ (in kgs^{-1}) and the calorific value ΔH_{dis} of diesel of about 46 $MJkg^{-1}$:

$$\dot{Q} = \alpha \dot{M}_{dis} \Delta H_{dis} \tag{21}$$

A typical variation of the diesel mass M_{dis} (in kg) with time t (in s) is shown in Fig. 3 with the following curve fitted:

$$M_{dis} = -0.0291t + 48.6 \tag{22}$$

Six tests with four on a circular pan and two on the square trays were carried out with a summary shown in Table 1. The mass of diesel burnt was from 6 kg to 6.4 kg. The air temperatures outside the chamber but inside the hall varied from 8.5°C to 15°C.

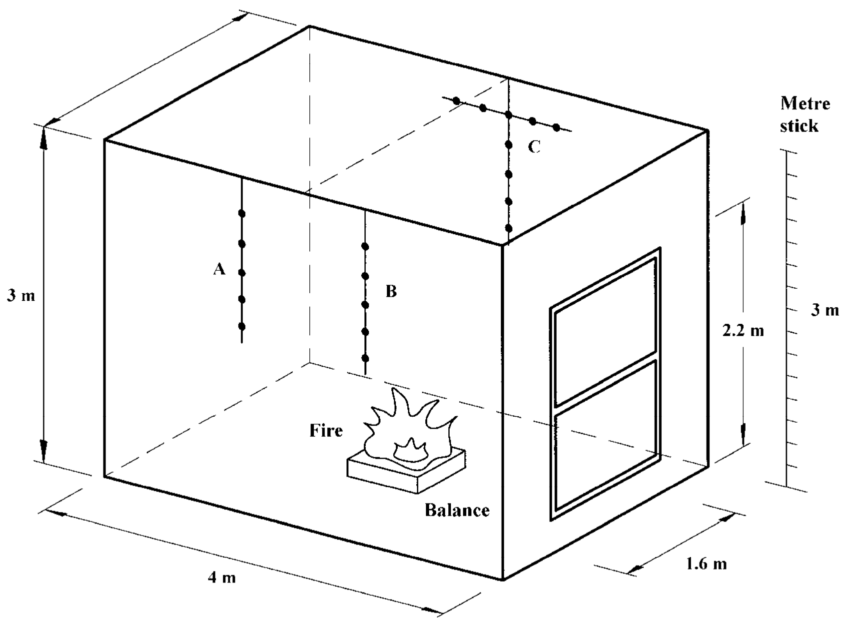


Fig. 2: The chamber

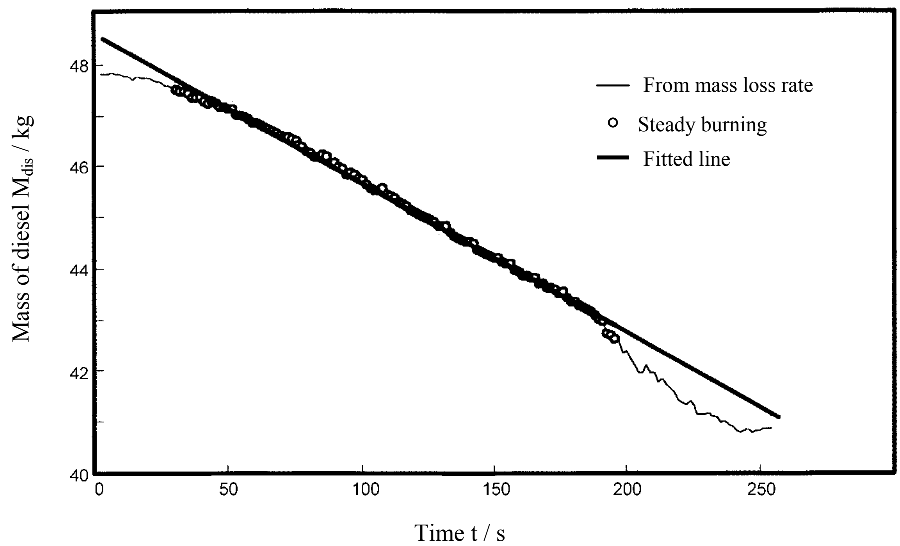


Fig. 3: Heat release rate of fuel

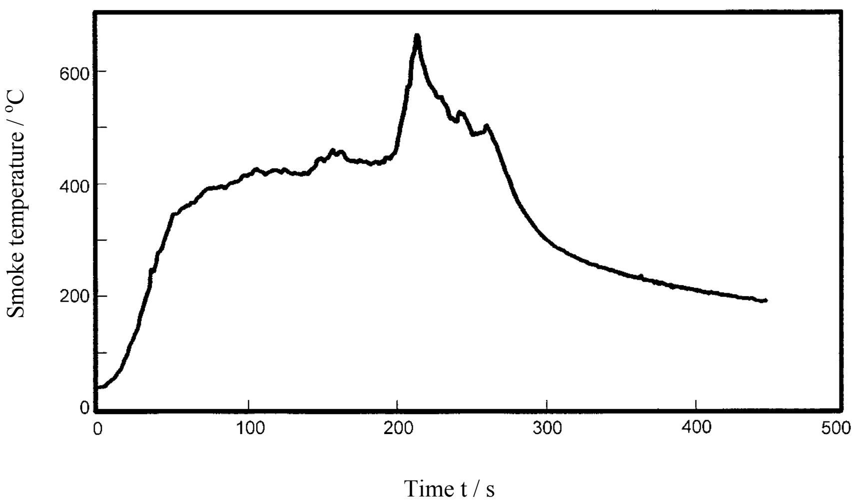


Fig. 4: Typical smoke layer temperature

Table 1: Summary of results

Test	Fire	Mass of diesel burnt / kg	Hall temp. / °C	Ventilation height H_v / m	Ventilation factor $A_v\sqrt{H_v}$ / $m^{5/2}$	Height to neutral plane of the vent / m	Height above neutral plane of the vent / m	Burning time / s	Average temp. of room at steady burning / °C	Flashover occurred?	Critical heat release rate $\dot{Q}_f$ / kW
1	C2	6.1	9.5	1.74	3.67	1.0 to 1.1	0.6	288	375	No	1040
2	C2	6	9.5	1.6	3.24	0.9 to 1.0	0.6	267	496	No	1040
3	C2	6.3	10.2	0.89	1.34	0.4 to 0.5	0.5	303	> 600	Yes	1020
4	C2	6.1	10.2	0.72	0.98	0.3 to 0.4	0.4	296	> 600	Yes	880
5	S2	6	8.5	2.2	5.22	1.5 to 1.6	0.6	1281	160	No	350
6	S1	6.4	15	1.2	2.1	0.7 to 0.8	0.5	312	> 600	Yes	1310

The ventilation height of the chamber varied from 0.72 m to 2.2 m, giving the ventilation factor varying from 0.98 $m^{5/2}$ to 5.22 $m^{5/2}$. The fuel was burnt with the height of the neutral plane observed and recorded. The burning times were from 267 s to 1281 s. Whether flashover occurred or not was observed with the critical heat release rate for flashover measured.

A typical variation of smoke layer temperature in the chamber is shown in Fig. 4.

5. DISCUSSION

The critical heat release rate Q_f for flashover was measured and compared with the three correlation equations as shown in Fig. 5. Experimental data with flashover occurred are also shown. From the experimental studies, the heat release rate predicted by CFAST [12] at 10 minutes (or 600 s) was taken as Q_f and shown also in the figure.

Note that for large openings, Thomas equation gives:

$$\dot{Q}_f = 17.4 A_v \sqrt{H_v} + 43.3 A_T \qquad (23)$$

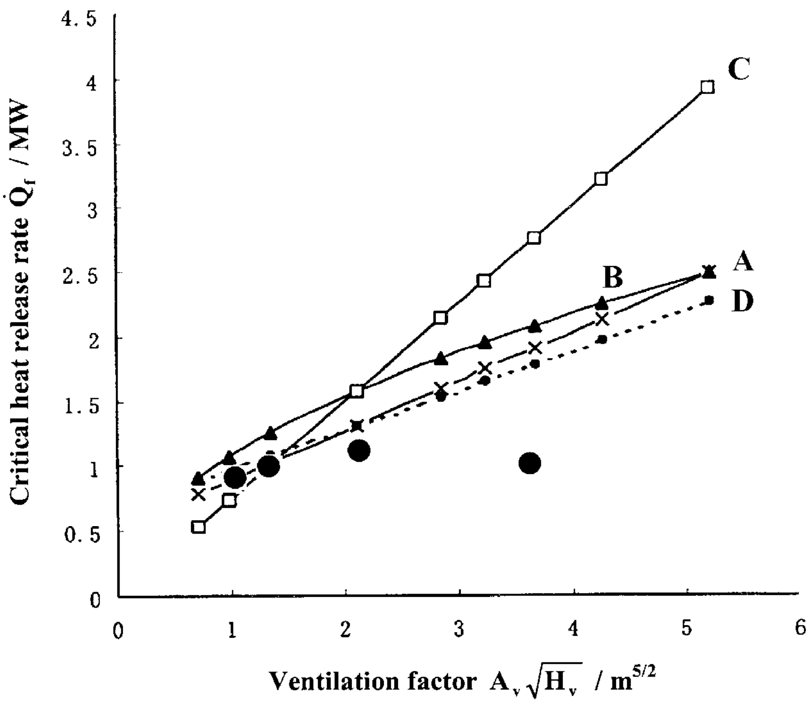
From this study, a modified equation can be recommended:

$$\dot{Q}_f = a A_v \sqrt{H_v} + b A_T \qquad (24)$$

where a = 378 $kWm^{5/2}$ and b = 7.8 kWm^{-2} for small openings with ventilation factor from 0 $m^{5/2}$ to 6 $m^{5/2}$; and a = 17.4 $kWm^{5/2}$ and b = 43.3 kWm^{-2} for big openings with ventilation factor from 15 $m^{5/2}$ to 7.5 $m^{5/2}$.

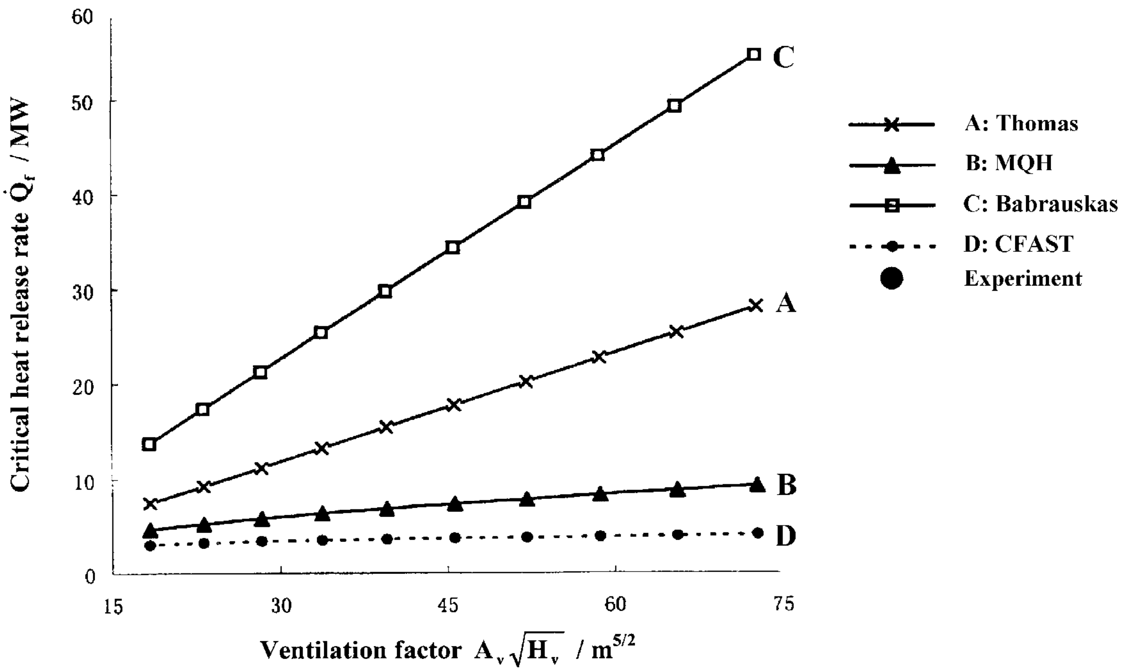
6. CONCLUSION

Three correlation equations on estimating the critical heat release rates for flashover to occur in a chamber are assessed by full-scale burning tests. These are equations due to Babrauskas [4], MQH [15] and Thomas [14]. Results are also compared with those predicted by the two-layer zone model CFAST [12]. From the studies, an equation was proposed for calculating the critical heat release rate for flashover in a small chamber with the ventilation factor for large openings taken into account. This will be helpful in estimating the possibility of flashover in small chambers such as a retail shop. Appropriate fire services installation to be provided can then be considered.



(a) Small opening

Fig. 5: Critical heat release rates



(b) Large opening

Fig. 5: Critical heat release rates

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