Thermal Empirical Equations for Post-Flashover Compartment Fires

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ABSTRACT

Many useful correlation equations derived for estimating the heat release rate are believed to be adequate in fire engineering application. However, heat release rates in deriving those equations were mainly based on estimating mass loss rate of fuel. Flashover in a compartment fire had been studied experimentally on gasoline pool fires with results on heat release rate reported earlier. Transient heat release rates were measured by oxygen consumption calorimetry. The gas temperature curves at different locations in the room were measured instantaneously. Correlation equations on heat release rates with gas temperature reported in the literature will be reviewed and justified with the experimental results. It was observed that heat release rate estimated were lower than the experimental measurement.

KEYWORDS: post-flashover, compartment fires, empirical equation.

NOMENCLATURE LISTING

A_w	total wall area of compartment (m)
A_v	area of ventilation opening (m)
C_p	specific heat capacity of gas (J/kg·K)
h_v	height of ventilation opening (m)
m_A	constant related to total heat release rate (kW·°C^{-1})
m_{AL}	constant related to heat lost (kW·°C^{-1})
m_{AV}	constant related to ventilation provision heat lost (kW·°C^{-1})
m_f	slope of fitted line
$\dot{m}_a$	air flow rate through the ventilation opening (kg·s^{-1})
$\dot{m}_p$	fuel mass loss rate (kg·s^{-1})
$\dot{q}$	heat release rate of fire (kW)
$\dot{q}_{max}$	maximum heat release rate measured (kW)

$\dot{q}_L$	heat lost rate (kW)
T_f	fire temperature (°C)
T_{fmax}	maximum fire temperature measured (°C)
T_o	air temperature of hall (°C)
t_B	burning time of fuel (s)
V_f	ventilation factor (m$^{5/2}$)
W_v	width of ventilation opening (m)

Greek

Δh_c	effective calorific value of fuel (MJ·kg^{-1})
σ	Stefan-Boltzman constant
ε_f	gas emissivity

INTRODUCTION

Big post-flashover [1] building fires were observed in big cities in the Far East. Taking Hong Kong [2] as an example, these big fires occurred in old factory buildings built 40 years ago. Possible reasons are firstly some factories for light plastics industry are starting to move back to Hong Kong. Secondly, such industrial buildings are now functioning as mini-warehouses. These old buildings are used as storage areas with much more combustibles. However, such buildings are not regarded as warehouses without adequate fire protection. Three big post-flashover fires occurred had already killed four firemen in the past few years. Therefore, flashover should be studied properly, particularly with so many modern materials used.

Works on flashover phenomenon reported in the literature mainly based on estimating air flow rate across opening in the room fire. These included pioneer works by Kawagoe [3] on hydrostatic models to give a relation on ventilation factor. Many other works followed [4–6] with experimental data reported in the

literature on deriving, assessing or verifying useful design empirical equations. Although there had been many studies on flashover fire, the understanding is still on thermal aspects. This is because firstly there are thousands of intermediate combustion chemical reactions while burning the fuel. Secondly, turbulent flow in air mixing is difficult to model. Thirdly, thermal radiation heat fluxes cannot be calculated accurately without measuring empirical parameters. In those works, heat release rate used to be assessed by the fuel mass loss rate. Flashover was commonly determined by observing whether flame came out of the doors. Results might be different if the heat release rates are measured oxygen consumption calorimetry, e.g. Ref. [7].

A series of full-scale burning tests on flashover in compartment fires with heat release rate measured by oxygen consumption calorimetry were performed and reported [8]. Results were applied to assess the correlation equations on the minimum heat release to flashover. Those results will be used further in this paper on studying thermal aspects of post-flashover fires. Transient gas temperatures measured at different locations of the room will be used to justify the transient heat release rate measured by oxygen consumption. Results are then compared with empirical equations reported in the literature.
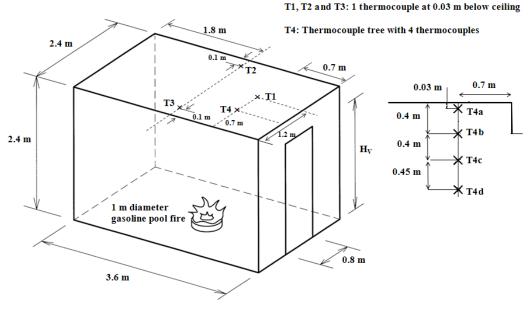

Fig. 1. The room calorimeter.

FULL-SCALE BURNING TESTS

A room calorimeter of length 3.6 m, width 2.4 m and height 2.4 m as shown in Fig. 1 was constructed with bricks in a full-scale burning hall at Northeast China. A door with fixed width W_v of 0.8 m but varying height h_v from 0.9 m to 1.95 m was provided. Ventilation factor can be adjusted from 0.68 $m^{5/2}$ to 2.18 $m^{5/2}$. Six sets of tests, labeled as A1 to A6 were carried out [8] with different values of H_v shown in Table 1. Tests A1 to A6 were for rectangular openings with height longer than the width. Opening arrangements for the tests are shown in Fig. 2.

A gasoline pool fire of 1 m diameter was placed at the room centre. The fuel volume was 1500 cm^3 to give a burning period t_B varying from 422 s to 621 s for tests with different ventilation provisions. Air temperature of the experimental hall T_o varied from 15 °C to 16 °C.

There are 7 thermocouples with 1 each at T1, T2 and T3, and 4 labeled as T4a to T4d at T4 as in Fig. 1. Transient gas temperatures were measured and shown in Fig. 3. Type-K thermocouple of 3 mm diameter able to stand up to 1000 °C was used for measuring post-flashover fire temperatures.

Transient heat release rates $\dot{q}$ in the room fire were measured by the oxygen consumption method with results shown in Fig. 4. Uncertainty of the heat release rate was calculated to be within 10 % as reported earlier.

Flashover was determined by when flames coming out of the opening. From the transient curve on $\dot{q}$, the minimum heat release rate was determined by two criteria: gas temperature next to ceiling at 600 °C or radiative heat flux of 20 kW·m^{-2}. The minimum heat release rate for flashover were then taken out on justifying correlation equations on the minimum heat release rates for flashover with the ventilation factor by Babrauskas [5,6], Thomas et al. [9,10], Quintiere et al. [11,12] and Morgan [13]. It was observed that experimental results lying close to the equation derived by Babrauskas [5,6], within the range of 30 % to 70 % of air intake rate for stoichiometric combustion. This set of equations [5,6] is now taken out and justified on temperature estimation for post-flashover fires in this presentation.

Table 1. Summary of results.

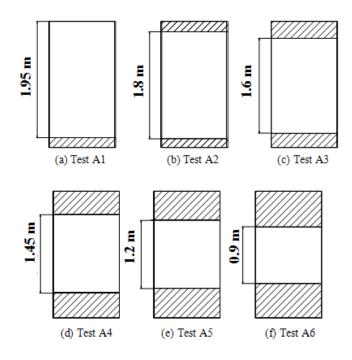	Test number / Parameters			A1a	A1b	A2a	A2b	A3a	A3b	A4a	A4b	A5a	A5b	A6
Ventilation height h_v / m			1.95		1.8		1.6		1.45		1.2		0.9
Height of vent bottom above floor / m			0		0		0		0.25		0.375		0.525
Ventilation factor V_f / m$^{5/2}$			2.18		1.93		1.62		1.4		1.05		0.68
Ambient air temperature T_o °C			15	15	15	15	16	16	15	15	16	16	16
Burning time t_B / s			621	488	472	556	547	524	566	531	452	422	608
Maximum heat release rate measured $\dot{q}_{max}$ / kW			2642	2632	2496	2460	2112	2354	1996	1776	1335	1306	934
Maximum gas temperature T_{fmax} / °C			806	818	791	799	760	809	798	750	751	710	675
m_A /kW·°C^{-1}	30 %	m_{AV}	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69
		m_A	1.55	1.57	1.44	1.46	1.28	1.38	1.29	1.20	1.09	1.01	0.84
	50 %	m_{AV}	1.14	1.14	1.01	1.01	0.85	0.85	0.74	0.74	0.55	0.55	0.36
		m_{AL}	0.86	0.89	0.83	0.85	0.77	0.87	0.85	0.76	0.76	0.68	0.62
		m_A	2.00	2.03	1.84	1.86	1.62	1.72	1.59	1.49	1.31	1.23	0.98
	70 %	m_{AV}	1.60	1.60	1.42	1.42	1.19	1.19	1.03	1.03	0.77	0.77	0.50
		m_A	2.46	2.49	2.25	2.27	1.96	2.06	1.88	1.78	1.53	1.45	1.12
Fitted line	m_f / kW·°C^{-1}		3.09	3.09	2.65	2.85	2.50	2.50	2.37	2.28	1.93	1.89	1.65
	R^2		0.9133	0.9290	0.8590	0.8856	0.8050	0.8224	0.8512	0.8202	0.7626	0.7486	0.7374

Fig. 2. Opening arrangements.

GAS TEMPERATURES

A thermal balance equation was proposed by Babrauskas [5,6] on the heat generation rate $\dot{q}$, air flow rate $\dot{m}_a$, fire temperature T_f, ambient air temperature T_o, heat lost $\dot{q}_L$ and specific heat capacity C_p of air as:

$$\dot{q} = \dot{m}_a C_p (T_f - T_o) + \dot{q}_L \tag{1}$$

Note that T_f is the flame temperature ejecting out of the opening. The gas temperature in the compartment near the ceiling is assumed to equal to T_f for a post-flashover fire.

The heat generation term $\dot{q}$ can be expressed in terms of fuel mass loss rate $\dot{m}_p$ and effective calorific value Δh_c as:

$$\dot{q} = \dot{m}_p \Delta h_c \tag{2}$$

The air flow rate through an opening of area A_v and height h_v is:

$$\dot{m}_a = 0.5 A_v (h_v)^{0.5} \tag{3}$$

Note that $A_v (h_v)^{0.5}$ is the ventilation factor relating to $\dot{q}$ [5,6].

The heat loss can be expressed in terms of wall area A_w, gas emissitivity ε_f of 0.5 and Stefan-Boltzman constant σ of 5.67×10^{-11} kW·m^{-2}·K^{-4}.

$$\dot{q}_L = \varepsilon_f \sigma (T_f^4 - T_o^4)(0.4 A_w) \tag{4}$$

This gives:

$$\dot{q} = m_A (T_f - T_o) \tag{5}$$

Note that there are two parts of the result m_A as in the above equation.

$$m_A = m_{AV} + m_{AL} \tag{6}$$

The first part m_{AV} is relating to ventilation provision given by Eq. 3. The second part m_{AL} is related to heat lost given by Eq. 4.

$$m_{AV} = 0.5 A_v h_v^{0.5} C_p \tag{7}$$

$$m_{AL} = \varepsilon_f \sigma (0.4 A_w)(T_f + T_o)(T_f^2 + T_o^2) \tag{8}$$
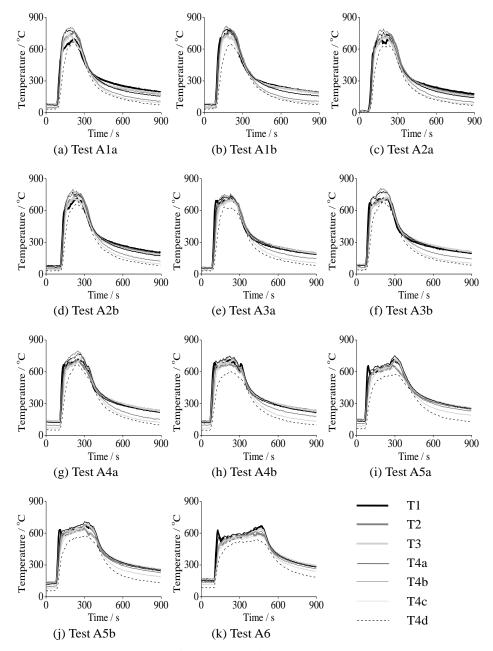
Fig. 3. Measured gas temperatures.

The values of T_f were different for each test with m_{AV}, m_{AL} and m_A estimated separately. Further, the values of A_v, h_v, A_w, and T_o were also different. Putting numerical values of C_p of 1.05 kJ·kg^{-1}·K^{-1} and V_f, for example of 2.18 m$^{5/2}$ as in Test A1a to Eq. 7, m_{AV} is 1.145 kW·°C^{-1}. Putting A_w of 44.52 m^2, σ of 5.67×10^{-11} kW·m^{-2}·K^{-4}, ε_f of 0.5 as used before by Babrauskas and Williams [5] which was demonstrated to be a good estimation for calculating heat release rate, T_f of 1079 K and T_0 of 288 K for Test A1a into Eq. 8 gives m_{AL} of 0.86 kW·°C^{-1}. Substituting m_{AV} and m_{AL} into Eq. 6, this gives m_A of 2.00 kWm^{-2}.
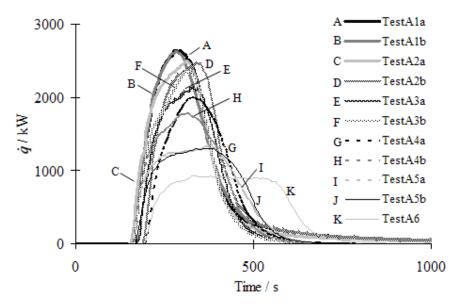

Fig. 4. Transient heat release rates.

DISCUSSION

Values of maximum heat release rate $\dot{q}_{max}$ for the tests are plotted against the maximum gas temperature rise $(T_{fmax} - T_o)$ among all measured 7 points at T1 to T4. Maximum gas temperature was at thermocouple T4b (position shown in Fig. 1) for tests A1a to A4b, and T4a for Tests A5b and A6. The following line of correlation coefficient R^2 of 0.649 is fitted by the method of least square.

$$\dot{q}_{max} = 2.97(T_{fmax} - T_o) \tag{9}$$

Experimental data on $\dot{q}_{max}$ and $(T_{fmax} - T_o)$ and the above line are shown in Fig. 5. As shown in Table 1, the values of m_A for the 6 sets of tests lie between 0.84 kW·°C^{-1} for Test A6 with 30 % stoichiometric burning to 2.49kW·°C^{-1} for Test A1b with 70 % stoichiometric burning. Analytical results given by Eq. 5 with m_A of 0.84 kW·°C^{-1} 2.49kW·°C^{-1} are also plotted in Fig. 5 for comparison.

It is clearly observed that experimental heat release rates measured by the oxygen consumption method are much higher than the estimated values.

In addition, the transient values of $\dot{q}$ are plotted against the corresponding transient $(T_f - T_o)$ on the set of curve with T_{fmax} for all six sets of tests. Again, these gas temperatures were measured at thermocouple T4b for Tests A1a to A4b, and T4a for Tests A5b and A6.

The following line fitted by the method of least square for each test with slope m_f is found for the experimental data:

$$\dot{q} = m_f (T_f - T_o) \tag{10}$$

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Values of m_f and the corresponding correlation coefficient R^2 for the six sets of tests are shown in Table 1. Values of m_f are lying from 1.65 kW·°C^{-1} for test A6 to 3.09 kW·°C^{-1}for Tests A1a. These lines are plotted together with analytical results for each test given by Eq. 5 in Fig. 6.

The range of validity given by Eq. 6 for m_A lying between $(0.6\ m_{AV} + m_{AL})$ and $(1.4\ m_{AV} + m_{AL})$ are also plotted in Fig. 6.
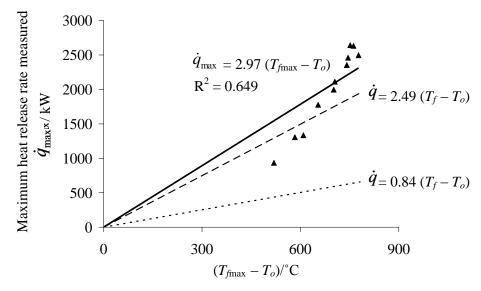

Fig. 5. Maximum heat release rate against maximum gas temperature.

In view of the above study, the thermal aspects on relating gas temperature with heat release rate measured by oxygen consumption calorimetry can be studied by the thermal balance equation. In general, heat release rates estimated by the analytical equation are smaller than experimental results. This is very obvious for the air flow rate through the door was estimated by Eq. 3. However, estimated heat release rate agreed better with experiment when the air intake rate is higher. The slope m_A are closer to m_f for higher air intake rate in view of Table 1.

CONCLUSION

Heat release rates for flashover fires in a small chamber were studied experimentally with oxygen consumption calorimetry. The correlation equations [5,6] on relating the heat release rates to gas temperature at post-flashover fires were justified by full-scale burning tests at different ventilation factors. It is observed that the estimated heat release rates were lower than the experimental measurement. Air intake rate might be higher to give more oxygen for combustion. This point should be considered in applying empirical correlation for estimating heat release rate [14].
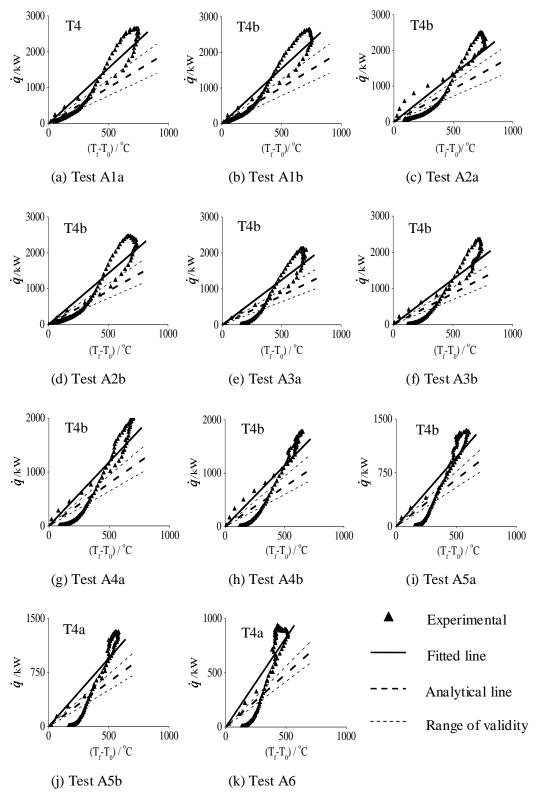
(a) Test A1a (b) Test A1b (c) Test A2a

(d) Test A2b (e) Test A3a (f) Test A3b

(g) Test A4a (h) Test A4b (i) Test A5a

(j) Test A5b (k) Test A6

Fig. 6. Transient results on the set of data with maximum gas temperatures.

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