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Predicting the Post-Flashover Temperature in a Compartment Fire Using Adiabatic Gas Temperature

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Keywords：Room temperature; compartment fire; adiabatic gas temperature.

ABSTRACT

The temperature in a compartment fire is crucial for fire risk assessment because it affects the growth of a compartment fire, the structural behavior of construction elements, etc. A previous model for predicting the temperature, both before and after flashover, using adiabatic gas temperatures has been developed. This model for predicting the temperature after flashover uses a correlation of heat release rate (HRR) at flashover. However, this model has only been verified by experimental data before flashover. This study modified the expression of HRR at flashover, and verified by experiment in an enclosure whose dimension is one third of an ISO 9705 chamber. The opening of the enclosure was 0.8 m high, and with different widths of 0.1, 0.2 or 0.3 m for considering the ventilation-controlled fire behavior after flashover. Fuels used were gasoline and iso-propanol. Experimental data showed that this model using the alternative expression can better predict the temperature after flashover. Additionally, the type of flashover was discussed with the prediction of post-flashover temperature.

INTRODUCTION

The prediction of gas temperature in a compartment fire is crucial for fire safety engineers to conduct fire risk assessment because the temperature affects the growth of a compartment fire, influences the structural behavior of construction elements, and causes panic and thermal injury to humans. This study analyzes the temperature in a compartment fire during post-flashover period because during which severe structural damage can occur. Both theoretical and experimental analyses were conducted in this study. Firstly, this study reviewed several previous investigations (Kawagoe, 1958, Pettersson and Magnuson, 1976, Babrauskas and Williamson, 1978, Delichatsios et al., 2009) on post-flashover temperatures. The model of Delichatsios et al. (2009) was particularly analyzed, because this study will extend this model. Secondly, the expression of heat release rate (HRR) at flashover, which is employed in the model of Delichatsios et al. (2009), was verified by experiments. Finally, this study provided an alternative expression of the HRR after flashover. The prediction of temperature after flashover using the alternative expression of the HRR after flashover was compared with experimental data.

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PREVIOUS STUDIES FOR PREDICTING THE TEMPERATURE WITHIN COMPARTENT FIRES AFTER FLASHOVER

Models of Kawagoe and Sekine (1963), Pettersson et al. (1976) and Babrauskas and Williamson (1978)

Several previous researches (Kawagoe, 1958, Pettersson and Magnuson, 1976, Babrauskas and Williamson, 1978, Delichatsios et al., 2009) have developed models to predict the likely temperature-time history of a potential compartment fire after flashover. The temperature inside the compartment is obtained by solving the heat balance (Eq. (1)) with the following assumptions:
(i) combustion is complete and takes place entirely within the confines of the compartment;
(ii) the temperature is uniform within the compartment at all times;
(iii) a single surface heat transfer coefficient may be used for the entire inner surface of the compartment; and
(iv) the heat flow to and through the compartment boundaries is uni-dimensional, i.e. corners and edges

are ignored and the boundaries are assumed to be 'infinite slabs'.

$$\dot{Q}_C = \dot{Q}_L + \dot{Q}_W + \dot{Q}_R + \dot{Q}_B \tag{1}$$

The models (Kawagoe and Sekine, 1963, Pettersson and Magnuson, 1976, Babrauskas and Williamson, 1978) employed several expressions, and only those expressions related to the model of Delichatsios et al. (2009) are described here. Equation (2) shows the rate of heat release. Pettersson et al. (1976) assume that the fire is ventilation-controlled and that the Kawagoe relationship (1958) can be applied directly. Assuming that $\dot{m}_g = \dot{m}_a$ (i.e. ignoring fuel volatilization), Eq. (3) shows the correlation of the rate of outflow of fire gases and inflow of air. Finally, the temperature inside the compartment, T_g, can be solved (Eq. (4)). The rate of inflow of air approximated by Eq. (3) was verified by Babrauskas and Williamson (1978), and demonstrated agreement with stoichiometric burning of wood. Drysdale (1998) noted that the remarkable agreement must be regarded as fortuitous in view of many simplifying assumptions that are made.

$$\dot{Q}_C = 0.09A\sqrt{H} \cdot \Delta H_c \tag{2}$$

$$\dot{m}_g = \dot{m}_a = 0.5A\sqrt{H} \tag{3}$$

$$T_g = \frac{\dot{Q}_C + 0.09c_p A\sqrt{H}T_0 + (A_T - A)\left(\frac{1}{\gamma_i} + \frac{\Delta x}{2k_1}\right)^{-1}(T_g - T_1) - \dot{Q}_R}{0.09c_p A\sqrt{H} + (A_T - A)\left(\frac{1}{\gamma_i} + \frac{\Delta x}{2k_1}\right)^{-1}} \tag{4}$$

The model of Delichatsios et al. (2009)

Delichatsios et al. (2009) developed a model for predicting the temperatures in a compartment fire for the periods of before and after flashover. In this model, a fire is considered in an enclosure having heat losses through the opening but not to the boundary of the enclosure, namely the enclosure boundary is adiabatic. Then, the gas temperature in the enclosure is defined from the following equation at quasi-steady conditions:

$$\dot{Q}_c = \dot{m}_g c_p \left(T_g^* - T_0\right) + \sigma A\left(T_g^{*4} - T_0^4\right) \tag{5}$$

For under-ventilated conditions, the mass inflow rate through the opening for the under-ventilated compartment fires is equal to $\dot{m}_a = 0.5AH^{1/2}$ (Eq. (3)). Since the heat of combustion of air is about 3000 kJ/kg, the heat release rate inside the enclosure can be calculated using Eq. (6). Ignoring the mass pyrolysis rates of fuel, Eq. (3) was also used in this model.

$$\dot{Q}_c = 1500A\sqrt{H} \tag{6}$$

Substituting Eqs. (3) and (6) into Eq. (5), the following energy balance equation is obtained for the case of under-ventilated fires. The adiabatic gas temperature therefore only depends on the opening geometry.

$$1500A\sqrt{H} = 0.5A\sqrt{H}c_p\left(T_g^* - T_0\right) + \sigma A\left(T_g^{*4} - T_0^4\right) \tag{7}$$

For well-ventilated conditions

$$\dot{Q}_c = \dot{m}_f \Delta H_c \tag{8}$$

$$\dot{m}_g = \frac{2}{3}C_d W \rho_0 \sqrt{2g\frac{T_0}{T_g^*}\left(1 - \frac{T_0}{T_g^*}\right)}\left(\frac{H}{2}\right)^{3/2} \tag{9}$$

Substituting Eqs. (8) and (9) into Eq. (5), an energy balance equation suitable for the case of over-ventilated fires is

$$\dot{Q}_c = \frac{2}{3}C_d W \rho_0 \sqrt{2g\frac{T_0}{T_g^*}\left(1 - \frac{T_0}{T_g^*}\right)}\left(\frac{H}{2}\right)^{3/2} c_p\left(T_g^* - T_0\right) + \sigma A\left(T_g^{*4} - T_0^4\right) \tag{10}$$

T_g is consequently obtained by substituting the T_g^* calculated from Eqs. (7) and (10) into Eq. (11).

$$\frac{T_g - T_0}{T_g^* - T_0} = 0.5\left(\frac{\sqrt{t}}{\sqrt{(k\rho c)_w}}\frac{\dot{Q}_c}{A_T\left(T_g^* - T_0\right)}\right)^{1/2} \tag{11}$$

MODEL MODIFIED FROM THE MODEL OF DELICHATSIOS ET AL. (2009)

The models shown in Sec.2.1 are complicated. Additionally, the models introduced in Sec. 2.1 and 2.2 applied the assumption by Pettersson et al. (1976), giving that the fire is ventilation-controlled and that the Kawagoe relationship (1958) can be applied directly. Drysdale (1998) has pointed out that should the fire happen to be in the fuel-controlled regime, then this assumption will lead to an overestimate of the rate of burning. Moreover, Babrauskas (1980) examined results from 33 room fires and found out that the HRR at flashover corresponded to flashover lay between 23% and 86% (average 50%) of the

HRR predicted by Eq.(3). Additionally, the heat of combustion of air, 3000 kJ/kg, is associated with stoichiometric burning (Drysdale, 1998). Drysdale (1998) suggested an average of the stoichiometric heat release rate at flashover, given Eq. (12).

$$\dot{Q}_c = 750A\sqrt{H} \tag{12}$$

This study modified Eq. (7) by replacing $1500AH^{1/2}$ with $750AH^{1/2}$ for the prediction of post-flashover compartment temperature, given Eq. (13). The mass rate of air inflow is accordingly expressed as $\dot{Q}_c/3000$ with the assumption of combustion heat of air about 3000 kJ/kg.

$$\dot{Q}_C = 750A\sqrt{H} = \frac{750A\sqrt{H}}{3000}c_p\left(T_g^* - T_0\right) + \sigma A\left(T_g^{*4} - T_0^4\right) \tag{13}$$

EXPERIMENTAL

Experimental design

An experimental compartment (see Figure 1) was produced in the scale of 1/3 ISO 9705 room test chamber to systematically examine the opening wide (10cm, 20cm and 30cm opening) effect. Fireproof cotton was set on the inner walls and ceiling to reduce the heat loss through the walls to produce a thermal environment with semi-adiabatic enclosure boundary. Fuels used were gasoline and iso-propanol and were filled in pans with diameter from 19, 22.5, 26, 30, to 40 cm to produce fires of different heat release rates and sootiness. The pans were located on 3/4 position of the central line on the floor. A thermocouple tree with nine thermocouples of distances of 10 cm from the top of the ceiling was set to measure the vertical temperature distribution history. Another two thermocouples, named “thermocouple-a” and “thermocouple-b”, were set 5 cm below the ceiling near an inner and outer corners. The series of temperature data will provide information of the flows. A total heat flux meter was located on the floor. The whole test chamber was put under the hood of ISO 9705 test facility to measure the heat release rate. After ignition by a small fire, the heat release rate, temperature near the opening/on the ceiling, heat flux onto the floor, mass loss rate of fuels and time to flashover were measured. Flashover is defined to be (1) the transition from a localized fire to the general conflagration within the compartment; (2) the transition from a fuel-controlled fire to a ventilation-controlled fire (1998). There should exist enough fuel in the compartment to be involved in pyrolysis until ventilation-controlled conditions are reached. The occurrence of flashover was consequently experimentally defined by the appearance of flame exiting out from the opening although flames can exit from an enclosure simply because they are long. Therefore, whether a flame exits out from the opening is caused by flashover or its length needs to be distinguished. The details of the method to confirm the occurrence of flashover is demonstrated in Appendix, and whether flashover occurred in each test was verified by this method. All the data related to flashover shown below were confirmed to be associated with flashover.

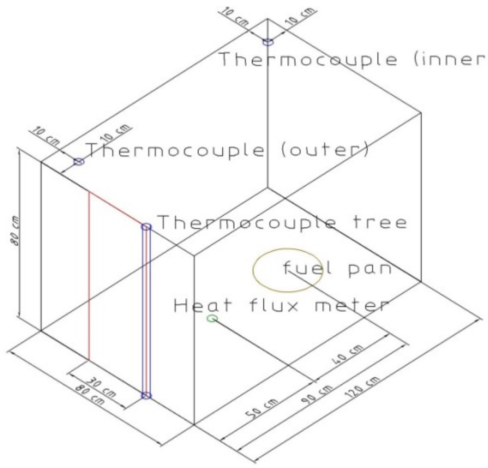

Fig. 1 Experimental set up.

Experimental results

Flashover did not occur in the cases of 22.5-cm-diameter iso-propanol fires and 19-cm-diameter gasoline fires with openings with all three widths. Figure 2 compares the predicted temperature history by the model of Delichatsios et al. (2009) and measured one for the 22.5-cm-diameter iso-propanol fires with 10 cm wide opening. The predicted temperatures were very close to the measured ones in the case shown in Fig. 2 and other cases without flashover (not shown). Therefore, the model of Delichasios et al. (2009) can adequately predict the temperature in a compartment fire without flashover.

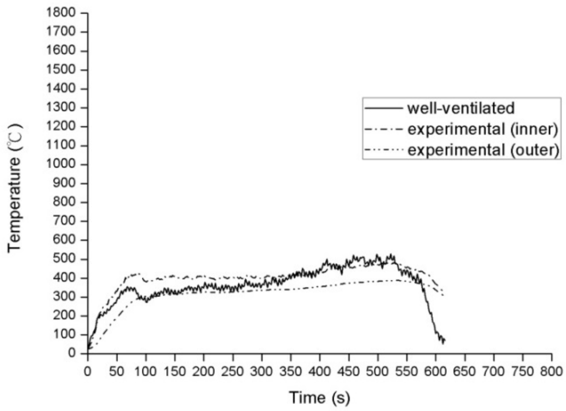

Fig. 2 Comparison of the predicted temperature history by the model of Delichatsios et al. (2009) and measured one for

22.5-cm-diameter iso-propanol fire with opening width of 10 cm.

Table 1 lists the time to flashover, HRR at flashover, measured and calculated for all the cases with flashover. Earlier time to flashover for narrower opening compartments fires was demonstrated. This experimental observation was consistent with Pierce and Moss (2007) who investigated the effect of door width on the growth of compartment fires. They (2007) pointed out that the hotter environment for narrower opening compartments was due to less smoky gas released and more heat feedback to the fuel.

Figure 3 compares the measured HRR at flashover and $750AH^{1/2}$ (Eq. (12)). Clearly, two groups of data were present. The gasoline tests in pans with diameters of 26 and 30 cm, and iso-propanol tests of 40 cm were ventilation-controlled while the others were fuel-controlled even flame exited from the openings. Francis and Chen (2012) described a “strong flashover” condition for the ventilation-controlled cases exhibiting a clear increase in the rate of temperature rise. The cases of gasoline fires with diameters of 26 and 30 cm and iso-propanol fires of 40 cm clearly corresponded to the “strong flashover” condition (type 3 in Francis and Chen (2012)). They (2012) also introduced a “weak flashover” condition for the fuel-controlled cases with flashover although flames exited from the openings. The cases of gasoline fires with diameters of 22.5 cm and iso-propanol fires of 26 and 30 cm clearly corresponded to the “weak flashover” condition (type 3A in Francis and Chen (2012)).

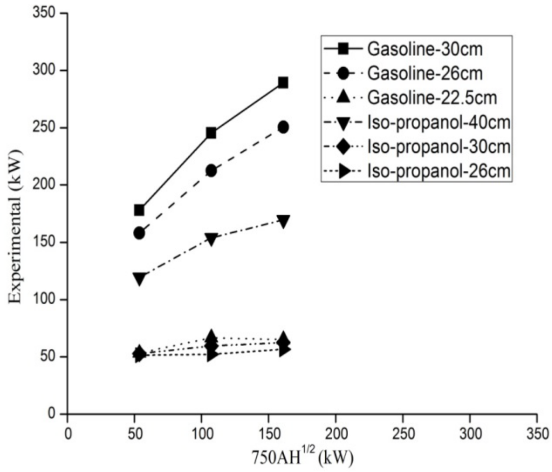

Fig. 3 Comparison of the measured HRRs at flashover and 750AH1/2.

Table 1. The time to flashover, HRR at flashover, measured and calculated for all the cases with flashover.

Fuel	Diameter of fuel pans (cm)	Opening width (cm)	$AH^{1/2}$	Time to flashover (s)	HRR at flashover (kW)	
					Experimental	$750AH^{1/2}$
Gasoline	30	30	0.215	44±2	287.8±1.4	161.00
		20	0.143	39±1	247.7± 2.3	107.33
		10	0.072	41±1	179.1±1.1	53.67
	26	30	0.215	48±1	245.7±4.8	161.00
		20	0.143	46±2	208.1±4.4	107.33
		10	0.072	43±1	167.6±9.6	53.67
	22.5	30	0.215	229±6	64.6±0.5	161.00
		20	0.143	223±1	63.0±3.7	107.33
		10	0.072	153±9	54.0±0.6	53.67
Iso-propanol	40	30	0.215	82±2	167.3±2.3	161.00
		20	0.143	72±0	152.6±1.3	107.33
		10	0.072	70±0	119.9±0.6	53.67
	30	30	0.215	84±1	65.7±3.1	161.00
		20	0.143	84±1	59.8±0.3	107.33
		10	0.072	80±1	52.9±0.1	53.67
	26	30	0.215	189±1	56.0±0.6	161.00
		20	0.143	198±2	53.9±1.7	107.33
		10	0.072	150±2	51.2±0.3	53.67

Figures 4–9 compare the predicted temperature histories by the model of Delichasios et al. (2009), those by the model in this study and measured ones (experimental (inner) and (outer)) for all the flashover cases with opening width of 30, 20 and 10 cm. The predictions by Delichasios et al. (2009) included those temperatures before flashover (well-ventilated) and after flashover (under-ventilated), while the predictions before flashover were additionally extended for durations after flashover for further analysis. The time to flashover was highlighted in all the cases. Clearly, the model of Delichasios et al. (2009) can adequately predicted the temperature before flashover for all the cases. A possible reason is that the thermal environment can be regarded as adiabatic while the fires were small before flashover. The heat lost to the enclosure boundary can be neglected. However, the predictions of temperature after flashover using the original model of Delichasios et al. (2009) were too high. The model modified in this study (using Eq. (13)) better predicted the temperatures in some cases, while the model of Delichasios et al. (2009) using well-ventilated equation (Eq. (5)) for post-flashover period also better predicted some cases.

The model modified in this study (using Eq. (13)) adequately predicted the post-flashover temperatures in all cases with opening width of 10 cm. However, when the opening was wider, the model modified in this study can still better predict the gas temperature in the “strong flashover cases” (see Figs. 4, 5 and 7) than the other two models, i.e. the original model of Delichasios et al. (2009) (under-ventilated) and the original model using Eq. (5) (well-ventilated) for the whole period of fire. However, the model developed in this study overestimated of the rate of burning as Drysdale (1998) has pointed out once the fire happens to be in the fuel-controlled regime because the model in this study still applied the assumptions of Pettersson et al. (1976) and Kawagoe relationship (1958) for ventilation-controlled fires. Furthermore, the model of Delichasios et al. (2009) using well-ventilated equation (Eq. (5)) for post-flashover period better predicted the temperatures in the “weak flashover” cases with opening width of 20 and 30 cm. The fires were fuel-controlled at flashover and were classed “weak flashover”. Conclusively, when the fires are ventilation-controlled with strong flashover, the model developed in this study can better predict the post-flashover gas temperatures in a compartment fire. When the fires are fuel-controlled with weak flashover, the post-flashover gas temperature predictions from the original model of Delichasios et al. (2009) using well-ventilated equation for the whole fire are close to the experimental data.

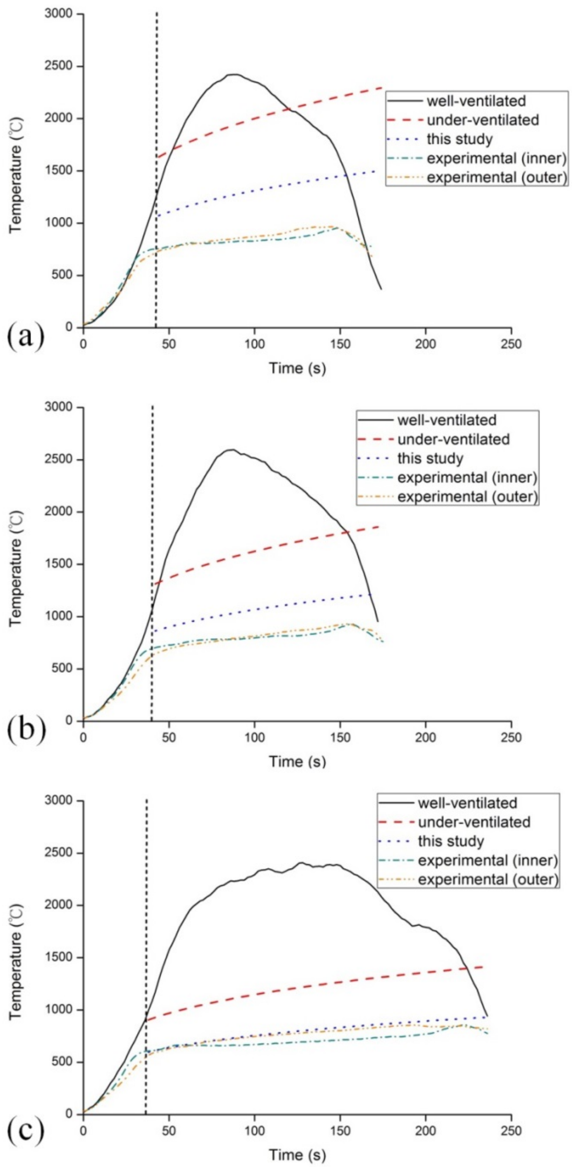

Fig. 4 The comparison of predicted temperature histories by the model of Delichasios et al. (2009) (well-ventilated and under-ventilated), those by the model in this study and experimental data (inner) and (outer) for 30-cm-diameter gasoline fires with opening width of (a) 30, (b) 20 and (c) 10 cm.

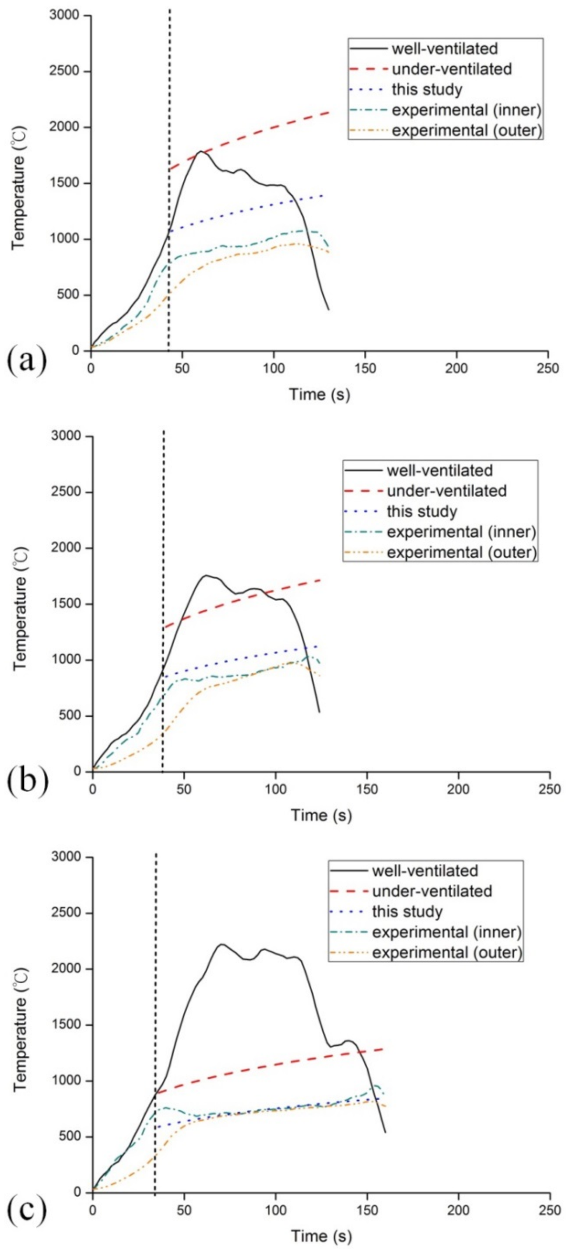

Fig. 5 The comparison of predicted temperature histories by the model of Delichasios et al. (2009) (well-ventilated and under-ventilated), those by the model in this study and experimental data (inner) and (outer) for 26-cm-diameter gasoline fires with opening width of (a) 30, (b) 20 and (c) 10 cm.

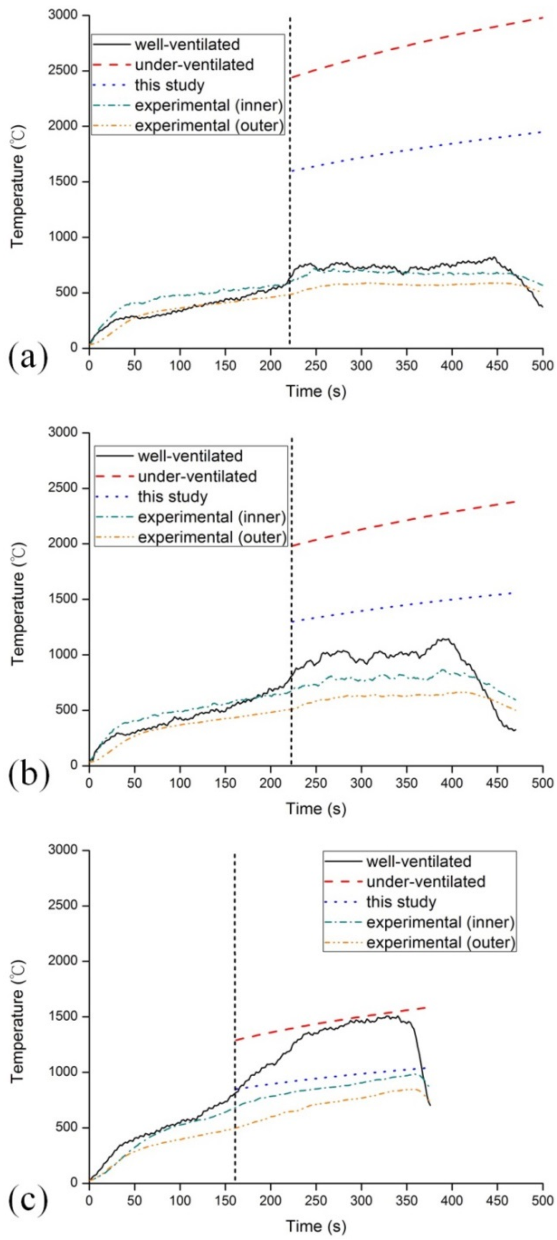

Fig. 6 The comparison of predicted temperature histories by the model of Delichasios et al. (2009) (well-ventilated and under-ventilated), those by the model in this study and experimental data (inner) and (outer) for 22.5-cm-diameter gasoline fires with opening width of (a) 30, (b) 20 and (c) 10 cm.

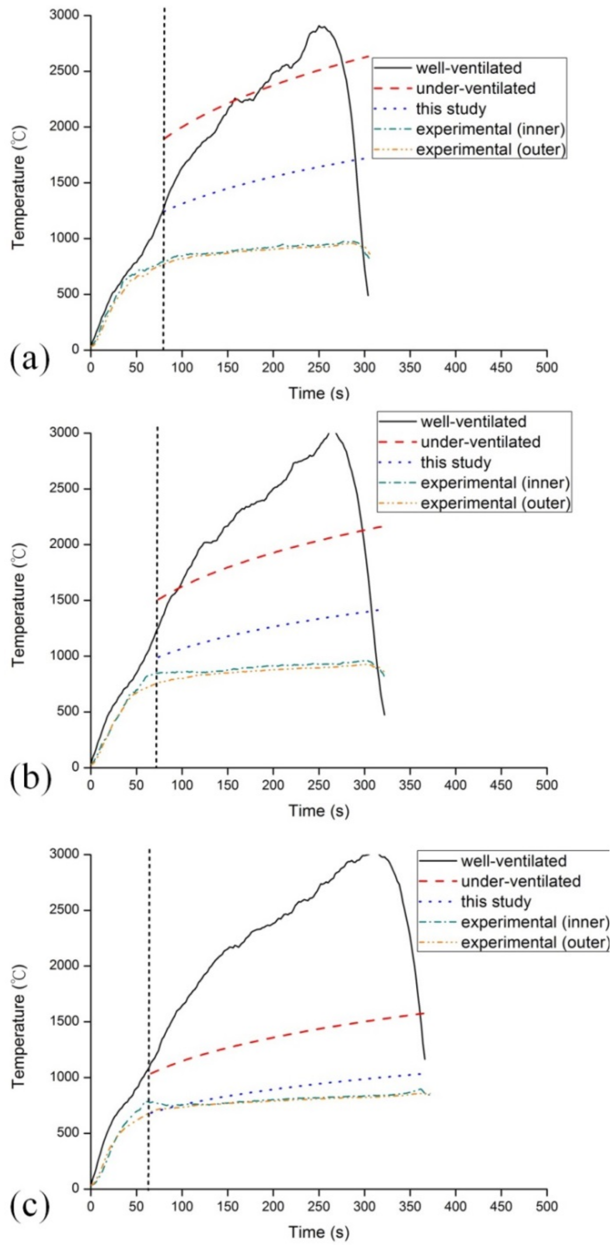

Fig. 7 The comparison of predicted temperature histories by the model of Delichasios et al. (2009) (well-ventilated and under-ventilated), those by the model in this study and experimental data (inner) and (outer) for 40-cm-diameter iso-propanol fires with opening width of (a) 30, (b) 20 and (c) 10 cm.

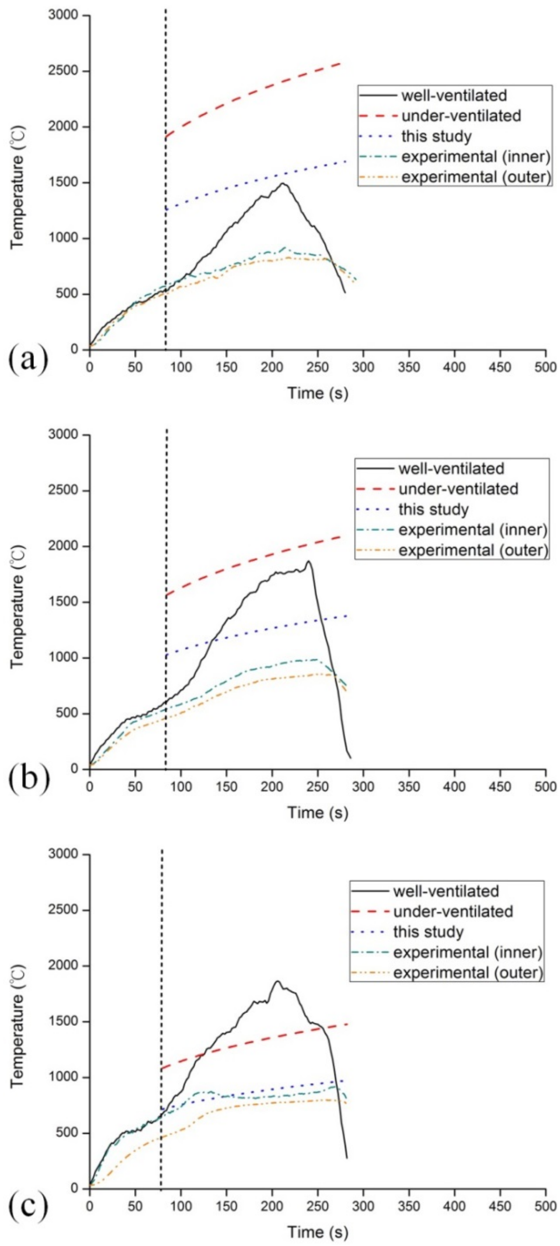

Fig. 8 The comparison of predicted temperature histories by the model of Delichasios et al. (2009) (well-ventilated and under-ventilated), those by the model in this study and experimental data (inner) and (outer) for 30-cm-diameter iso-propanol fires with opening width of (a) 30, (b) 20 and (c) 10 cm.

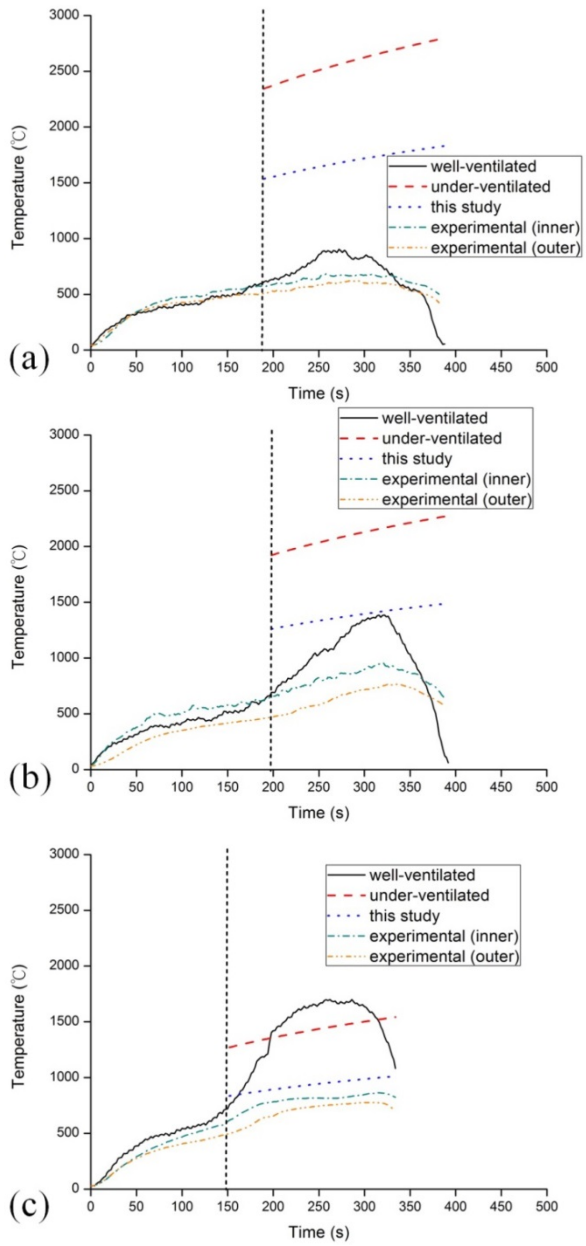

Fig. 9 The comparison of predicted temperature histories by the model of Delichasios et al. (2009) (well-ventilated and under-ventilated), those by the model in this study and experimental data (inner) and (outer) for 26-cm-diameter iso-propanol fires with opening width of (a) 30, (b) 20 and (c) 10 cm.

CONCLUSIONS

The model of Delichatsios et al. (2009) for predicting the temperature after flashover using adiabatic gas temperatures was verified and modified in this study. This study uses an alternative expression of heat release rate (HRR) at flashover, given $750AH^{1/2}$. The following conclusions were made.

(1)The condition of post-flashover period, i.e. ventilation- or fuel-controlled with strong or weak flashover, significantly influences the feasibility of applying a model for predicting the post-flashover gas temperature in a compartment fire.

(2)When the fires are ventilation-controlled with strong flashover, the model developed in this study can better predict the post-flashover gas temperatures in a compartment fire. When the fires are fuel-controlled with weak flashover, the post-flashover gas temperature predictions from the original model of Delichasios et al. (2009) using well-ventilated equation for the whole fire are close to the experimental data.

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APPENDIX

The occurrence of flashover was defined by the appearance of flame exiting out from the opening in this study. However, flames can exit from an enclosure simply because they are long. Therefore, to distinguish whether a flame exits out from the opening is caused by flashover or its length is necessary.

Figure A-1 shows the schematic of a flame exiting from an opening simply because the flame is long. The length of a flame (L_{flame}) in a compartment fire is close to its free-burning height ($L_{free\ burning}$) calculated by Equation A-1 (Drysdale, 1998) even the flame is deflected due to the ceiling of the compartment. When the flame exits out from the opening without the occurrence of flashover, both L_{flame} and $L_{free\ burning}$ exceed L1+L2. (L1 and L2 are the height of the compartment and horizontal distance between the pool fire and opening, respectively.)

$$L_{free\ burning} = 0.23\dot{Q}_c^{\frac{2}{5}} - 1.02D \qquad \text{(A-1)}$$

where $L_{free\ burning}$ is the flame height, $\dot{Q}_c$ is heat release rate and *D* is the diameter of a round pool fire.

However, when flashover occurs, the flame exiting from the opening is not caused by the free-burning flame length. Although L_{flame} is greater than L1+L2, $L_{free\ burning}$ is less than L1+L2.

Table A-1 shows the comparison of $L_{free\ burning}$ and L1+L2 in this experimental study. L1+L2 are equal to 1.7 m (see Fig. 1). Consequently, in all the tests in this study, flames exiting out from the opening were caused by flashover.

NOMENCLATURE

A	area of ventilation opening (m^2)
A_T	total area of enclosure minus opening area (m^2)
C_d	heat transfer coefficient (-)
C_p	specific heat (J/kgK)
H	height of opening (m)
k_1	constant (-)
L_{flame}	length of a flame (m)
$L_{free\ burning}$	free-burning flame height (m)
L1	height of compartment
L2	horizontal distance between pool fire and compartment opening
$\dot{m}_a$	mass rate of air inflow (kg/s)
$\dot{m}_g$	rate of gases out of enclosure (kg/s)
$\dot{m}_f$	mass pyrolysis rate of fuel (kg/s)
$\dot{Q}_B$	rate of heat storage in the gas volume (kW)
$\dot{Q}_C$	rate of heat release due to combustion (kW)
$\dot{Q}_L$	rate of heat loss due to replacement of hot gases by cold (kW)
$\dot{Q}_R$	rate of heat loss due to radiation (kW)
$\dot{Q}_W$	the rate of heat loss through the walls, ceiling and floor (kW)
T_g	gas temperature within compartment (K)
T_g^*	adiabatic gas temperature (K)
T_0	outside (ambient) temperature (K)
T_1	temperature (K)
W	width of opening (m)
γ_i	constant (-)
ρ_0	air density (kg/m^3)
Δx	constant (-)

Table A-1 The comparison of $L_{free\ burning}$ and L1+L2 in this experimental study

Fuel	Diameter of fuel pans (cm)	Opening width	Flame height at flashover (m)	L_1+L_2 (m)
Gasoline	30	30cm opening	1.64	1.7
		20cm opening	1.60	
		10cm opening	1.52	
	26	30cm opening	1.37	1.7
		20cm opening	1.31	
		10cm opening	1.14	
	22.5	30cm opening	0.99	1.7
		20cm opening	0.91	
		10cm opening	0.90	
Iso-propanol	40	30cm opening	1.38	1.7
		20cm opening	1.32	
		10cm opening	1.15	
	30	30cm opening	0.90	1.7
		20cm opening	0.87	
		10cm opening	0.82	
	26	30cm opening	0.89	1.7
		20cm opening	0.85	
		10cm opening	0.85	

絕熱狀態預測閃燃後室內溫度

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摘 要

若侷限空間發生火災，室內溫度為火災風險評估之關鍵因子，其影響火災成長情況及建築結構之變化等。先前研究於絕熱狀態下，建立閃燃前及閃燃後之室內溫度預測公式，而閃燃後之室內溫度係以閃燃時之熱釋放率為基礎進行預測。然而，此預測公式與實驗結果進行比對分析，僅閃燃前之預測公式符合實驗結果。因此，本研究提出修改閃燃時熱釋放率之公式，並以居室火災實驗結果進行驗證，該居室空間尺寸為三分之一 ISO 9705 標準房間，其開口尺寸高為 0.8 m，寬為 0.1、0.2、0.3 m，實驗燃料為汽油及異丙醇，實驗結果與修訂之閃燃後預測公式進行比對，結果顯示該預測公式將可更準確的預測閃燃後室內溫度。