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Experimental study of fuel sootiness effects on flashover

Kuang-Chung Tsai*, Hung-Hsiang Chen

Dept. of Safety, Health and Environmental Engineering, National Kaohsiung First University of Science and Technology, 2 Juoyue Road, Nantzu, Kaohsiung 811, Taiwan

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ABSTRACT

Previous fire safety studies have demonstrated that flashover can result in severe injure and death and heat radiating back to a fuel is an important mechanism. Fuel sootiness dominates in radiative heat transfer. However, empirical correlations from previous investigations did not consider the fuel sootiness but nevertheless generated reasonably good predictions of flashover. In this study, a series of experiments was employed to examine fuel sootiness effects on flashover. The fuels used, in the order of their sootiness, were gasoline, *n*-hexane, *iso*-propanol and methanol. These fuels were filled in circular pans 100–320 mm in diameter to generate fires with different heat release rates and levels of sootiness. The pans were in 1/3 the size of the ISO 9705 test chamber. After ignition, the heat release rate (HRR), temperature inside the chamber, as well as heat flux on the floor and time to flashover (t_{fo}) were determined. Experimental data show that HRR at flashover and t_{fo} were strongly corrected and their relationship was independent of the fuel burned. Although heat feedback to the floor increased as fuel sootiness increased, consequently enhancing the burning of sooty fuels, flashover occurs only when the HRR at flashover criterion is reached.

1. Introduction

Flashover is an indicative of untenable conditions within a room fire and of markedly increased risk to other rooms within a building [1]. Flashover can cause severe injure and death [2–6]. Due to the dangers posed by flashover, many studies have investigated this phenomenon.

1.1. The flashover phenomenon

Flashover is a very phenomenon during fire growth and generally occurs within confined spaces [7]. After ignition, a fire may grow by increasing the burning rate of the first item ignited, flames spreading to increase the burning area, and ignition of secondary fuels. During this process, hot, smoky gas, typically generated by flames, rises and forms a smoke layer at the ceiling, thereby increasing compartment temperature, especially that of upper surfaces. As a result, heat radiating from hot surfaces, the smoky layer, and other combustible materials may cause all combustible items in an enclosure to ignite simultaneously. This phenomenon, flashover, is considered the transition from a localized fire to a general conflagration within a compartment during which all fuel surfaces burn [7], resulting in a transition from a fuel-controlled fire to a ventilation-controlled fire. In addition, the heat generated by a fire and hot surfaces increase the temperature of all combustible items in a compartment, thereby increasing the amount of vaporized fuel. Some of these vapors are burned by a fire. Other unburned gases and vapors are released into the environment, most of which become trapped by a compartment's ceiling. When flashover occurs, these unburned gases and vapors above the fuel beds ignite suddenly. At roughly the time, flames typically emerge from windows and other openings.

Clearly, fuel volatiles generated from the fuel bed have an important role in flashover. Fuel bed heating dominates during the production of volatiles and the heat comes from the flame itself, hot surfaces in the upper part of an enclosure and hot combustion products trapped under a ceiling. Additionally, several studies have shown that a large proportion of the substantial amount of heat is from hot smoky combustion products by radiation [7]. Hasemi et al. [8] indicated that the onset of flashover is caused by heating of combustibles by smoky layer in their full-scale experiment. Orloff et al. [9], in their study of burning a polyurethane foam slab, predicted that the percentage of heat radiates from hot smoky combustion products was 85% although the relatively cooler lower layer generally absorbs radiating heat emitted from the hot, smoky layer. Cheung et al. [10] discussed the presence of soot radiation in numerical models, in addition to the radiation absorbed and emitted by combustion products, showing significant improvement of numerical predictions and better agreement with experimental data. The role of soot particles in fire growth is important.

* Corresponding author. Tel.: +886 7 6011000x2329; fax: +886 7 6011061.
E-mail address: tsaikc@ccms.nkfust.edu.tw (K.-C. Tsai).

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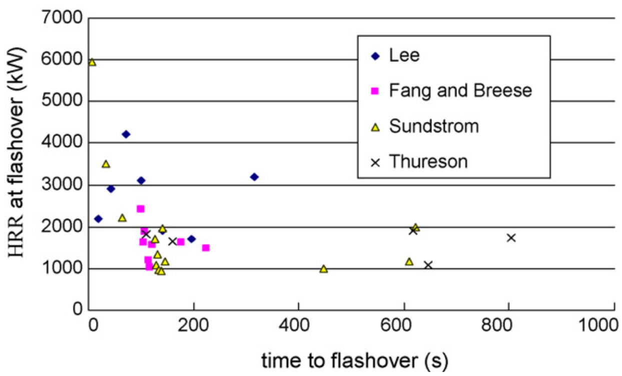

Fig. 1. Effect of time to flashover on the HRR required for flashover [3].

1.2. Working definitions of flashover

Qualitative definitions of flashover are impractical when designing fire safety facilities; thus, quantitative definitions are needed. Babrauskas and co-workers [1,11] called these quantitative definitions working definitions of flashover.

(i) Temperature and heat flux

Peacock et al. [1] summarized the determined temperature and heat flux at flashover from many previous studies. Most of these studies applied full-scale tests with compartments similar in size to the ISO 9705 test chamber [12] (3.64 m × 2.43 m × 2.43 m). Heselden et al. [13] used a small 1-m high compartment. Flashover onset was defined as flames exiting the compartment doorway or the ignition of newspaper on the compartment floor. The latter definition is based on the involvement of all combustible items during flashover. A ceiling temperature criterion of 600 °C and floor heat flux criterion of 20 kW/m^2 were determined. Meanwhile, a temperature criterion of 450 °C was carried out in the study of Heselden et al. [13].

(ii) Heat release rate (HRR)

Temperature and heat flux associate with flashover onset and can only be regarded as predicting indicators when prediction tools are reliable. The heat release rate (HRR) is measured directly from burning items and is easily estimated for specific fire scenarios. Babrauskas et al. [1,11], who analyzed data from several ISO 9705 room tests, showed that HRRs during flashover are 1975 ± 1060 kW. In addition, a HRR of 1 MW is the minimum rate needed for flashover.

Fig. 1 demonstrates the relationship between HRR at flashover and time to flashover, analyzed by Babrauskas et al. [11]. Experimental data are from four studies [11] using different burners to ignite fires and different wall lining materials. Notably, high HRRs are required for flashover during the first 2 min of a fire.

1.3. Criterion of minimum heat release rate to produce flashover

When designing fire safety facilities, applying lower bound estimates of important parameters is both practical and conservative. Several investigations determined the minimum HRR needed to produce flashover within a single compartment with a single door-like vent. Babrauskas [14] identified a flashover criterion of HRR based on a temperature increase of 575 °C in an experimental combustion model.

$$\dot{Q} = 750A\sqrt{h} \tag{1}$$

where $\dot{Q}$ is the minimum HRR needed to produce flashover, and A and h are vent area and height, respectively. Hägglund et al. [15], who obtained data using a two-zone model, suggested that the minimum HRR needed for flashover can be derived as

$$\dot{Q} = 1050A_T\left(\frac{1.2}{A_T/A\sqrt{h}} + 0.247\right)^3 \tag{2}$$

where A_T is the total surface area in the compartment. Thomas [16] applied the same parameters but assumed that the radiation loss is estimated to be 1/6 of the effective total area, A_T.

$$\dot{Q} = 7.8A_T + 378A\sqrt{h} \tag{3}$$

McCaffrey et al. [17] applied regression analysis to data from over 100 experiments, and demonstrated a correlation using an effective heat transfer coefficient to ceilings/walls h_k.

$$\dot{Q} = 740\sqrt{h_K A_T A\sqrt{h}} \tag{4}$$

Moreover, several studies [7] have focused on the effects of ventilation, the thermal properties of wall lining materials and the aspect ratio of a compartment. The HRR required for flashover increases as the ventilation factor, $A\sqrt{H}$, increases, for materials with a high effective heat transfer coefficient, h_K [18] and large compartment aspect ratio [19].

1.4. Theoretical analysis of zone models for predicting flashover

Thomas et al. [20] pioneered to regard flashover a case of thermal instability within a compartment, and developed a quasi-steady-state fire model by considering the energy balance of the hot layer at the ceiling. As a fire grows, the rates of heat generation and loss will change and can reach a critical stage in which any slight increase in the burning rate causes a substantial jump in both temperature and the burning rate. Hasemi [21], Bishop et al. [22], Holborn et al. [23], Graham et al. [24,25], Yuen and Chow [26] analyzed the instability of non-linear models. Here, the arguments presented by Graham et al. [24] are used in further discussion of flashover. The equation of energy conservation takes the form of heat balance [24]:

$$mC_p\,\frac{dT}{dt} = G - L \tag{5}$$

where the left side of Eq. (5) is the rate of change of internal energy of the hot layer, t is time, T is the smoke/hot zone temperature, m is the total mass of the hot layer and C_p as specific heat capacity. On the right side of Eq. (5), G and L are the net rate of heat gain and loss, respectively, from the hot zone [24].

$$G = \chi\Delta h_c\frac{A_f}{\Delta h_{vap}}[\dot{q}'' + \alpha_U\sigma(T^4 - T_0^4)] \tag{6}$$

where χ is combustion process efficiency, Δh_c and Δh_{vap} are combustion and vaporization heats of a solid fuel, respectively; A_f is the burning area; $\dot{q}''$ is the incident heat flux for the fuel bed; α_U is the radiation feedback coefficient from the hot layer and compartment walls at temperature T; σ is the Stefan–Boltzman constant; T_0 is the ambient temperature. The rate of heat loss from the smoke layer is given [22] by

$$\begin{aligned} L = {} & \frac{2}{3}C_d\rho_0A_v\sqrt{2gH_v'\frac{T_0}{T}\left(1-\frac{T_0}{T}\right)}C_p(T-T_0)(1-D) + [A_U-(1-D)A_v]h_c(T-T_w) \\ & +(1-D)A_vh_v(T-T_0) + \alpha_g\sigma[A_U-(1-D)A_v](T^4-T_w^4) \\ & +\alpha_g\sigma[A_L+(1-D)A_v-A_f](T^4-T_0^4) + \alpha_g\sigma A_f(T^4-T_f^4) \end{aligned} \tag{7}$$

where C_d is the discharge coefficient; g is the acceleration due to gravity; h_v and h_c are the convective heat transfer constant for the

Table 1
Time to ignition, HRR, heat flux and temperature measurements at flashover.

Fuel	Burning area (cm^2)	Time to flashover (s)	HRR at flashover (kW)	Heat flux at flashover (kW/m^2)	Temperature at the ceiling center at flashover (°C)
Gasoline	804	14	355	41.1	802.9
	476	26	182	56.5	858.6
	397	44	154	53.4	914.0
	283	76	133	44.1	834.8
	227	152	71	30.0	832.4
	177[a]	Not occur	35.7	14.5	591.3
n-Hexane	397	42	134	38.9	882.5
	283	60	124	37.8	859.9
	227	84	106	28.7	848.3
	177	190	84	38.3	948.0
	113	360	66	31.8	877.4
	79[a]	Not occur	21.6	3.83	331.4
iso-Propanol	804	37	97	23.3	896.6
	680	137	84	35.3	934.3
	624	180	78	28.4	866.7
	574	266	68	28.3	867.2
	478	718	62	25.7	703.9
	397[a]	Not occur	48.7	13.9	644.6
Methanol	1608	46	150	24.9	889.7
	1201	68	137	33.5	939.0
	1087	84	100	27.2	932.8
	1031	344	88	25.4	790.6
	983	860	67	25.9	843.9
	883[a]	Not occur	56.9	10.9	619.3

[a] The HRR, heat flux and temperature are the maximum among non-flashover tests.

vent and hot wall surfaces, respectively; A_v, A_U and A_L are the surface areas of the vent, wall surrounding the smoke layer and the lower zone, respectively; D is the height fraction of the thermal interface (thermal discontinuity plane) above the vent bottom and vent height; H_v' is the vent part through which hot gas flows; ρ_0 is air density; T_f and T_w are the temperatures of the fuel and walls surrounding the hot zone, respectively; and α_g is the emissivity of a gas layer. The last three items in Eq. (7) are the radiative heat transfer from the hot zone to the hot wall surfaces, cool zone and vent, and fuel bed areas, respectively. Clearly, α_g and α_U are related to fuel sootiness.

In these studies [20–26], Semenov's diagram of classical thermal explosion theory was applied to find solutions for the balance condition of curves of the gain function, G (Eq. (6)), and loss function, L (Eq. (7)). Notably, the intermediate solution of quasi-steady behavior is unsteady and any small perturbation results in large temperature changes. A critical temperature for flashover is obtained when a critical condition occurs.

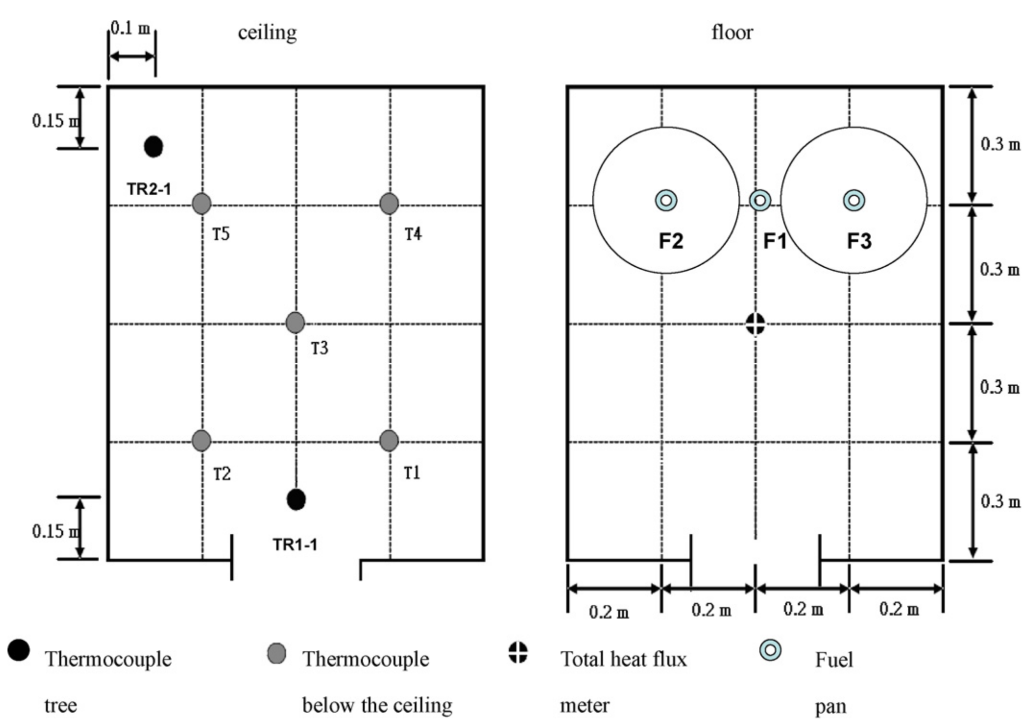

Fig. 2. Positions of thermocouples, thermocouple trees, total heat flux meter and fuel pans. The two pans with diameter of 320 mm were demonstrated as an example, generating 1608 cm^2 methanol fires.

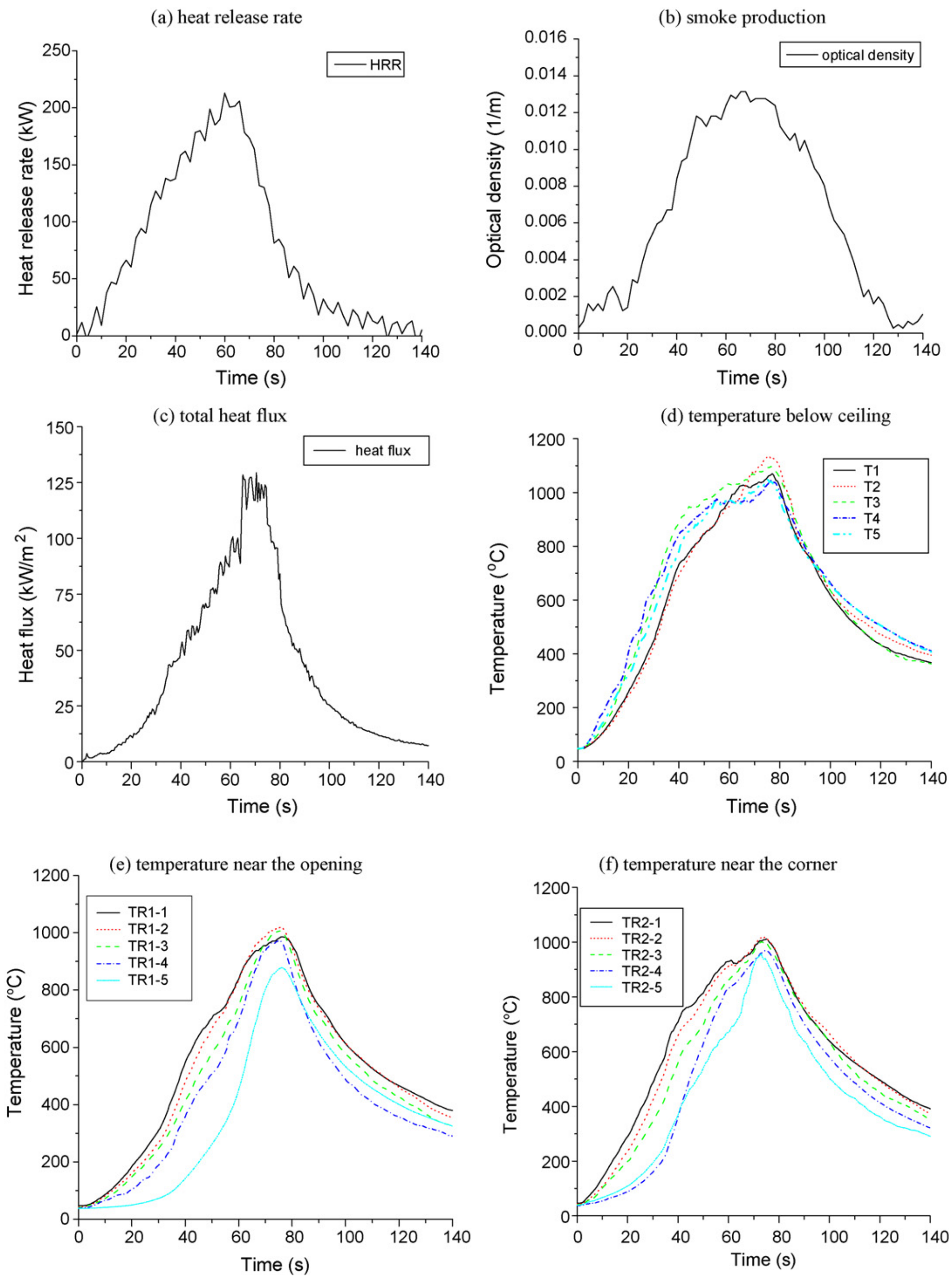

Fig. 3. (a–f) Time histories of HRR, smoke production, total heat flux on the floor, temperatures near the opening, near a corner and below the ceiling of a 397 cm^2 gasoline test.

In the work by Yuen and Chow [26], the heat transfer from compartment walls, particulate concentration in the hot layer and ventilation opening size are demonstrated to be the primary parameters that can lead to thermal instability and resulting flashover onset. Graham et al. [24] argued that the thermal inertia of walls, the fire area, radiative heat flux from the upper zone to the fuel bed, and heat loss rate significantly impact the occurrence of flashover and the time needed to produce flashover.

The mechanisms of flashover and their interactions are extremely complex. This study focuses on the effects of fuel sootiness. The theoretical investigations (Section 1.4) underline the importance of $\dot{q}''$, α_U and α_g in Eqs. (5)–(7), which determine the intensity of radiation from a flame, hot layer and smoky combustion products trapped under a ceiling. Radiation intensity is governed by fuel sootiness [27]. Although empirical correlations identified by experimental studies do not consider fuel sootiness, the minimum HRR to produce flashover can still be reasonably determined. Therefore, the importance of fuel sootiness warrants further investigation. In this study, a series of experiments was designed to systematically study the fuel sootiness effects.

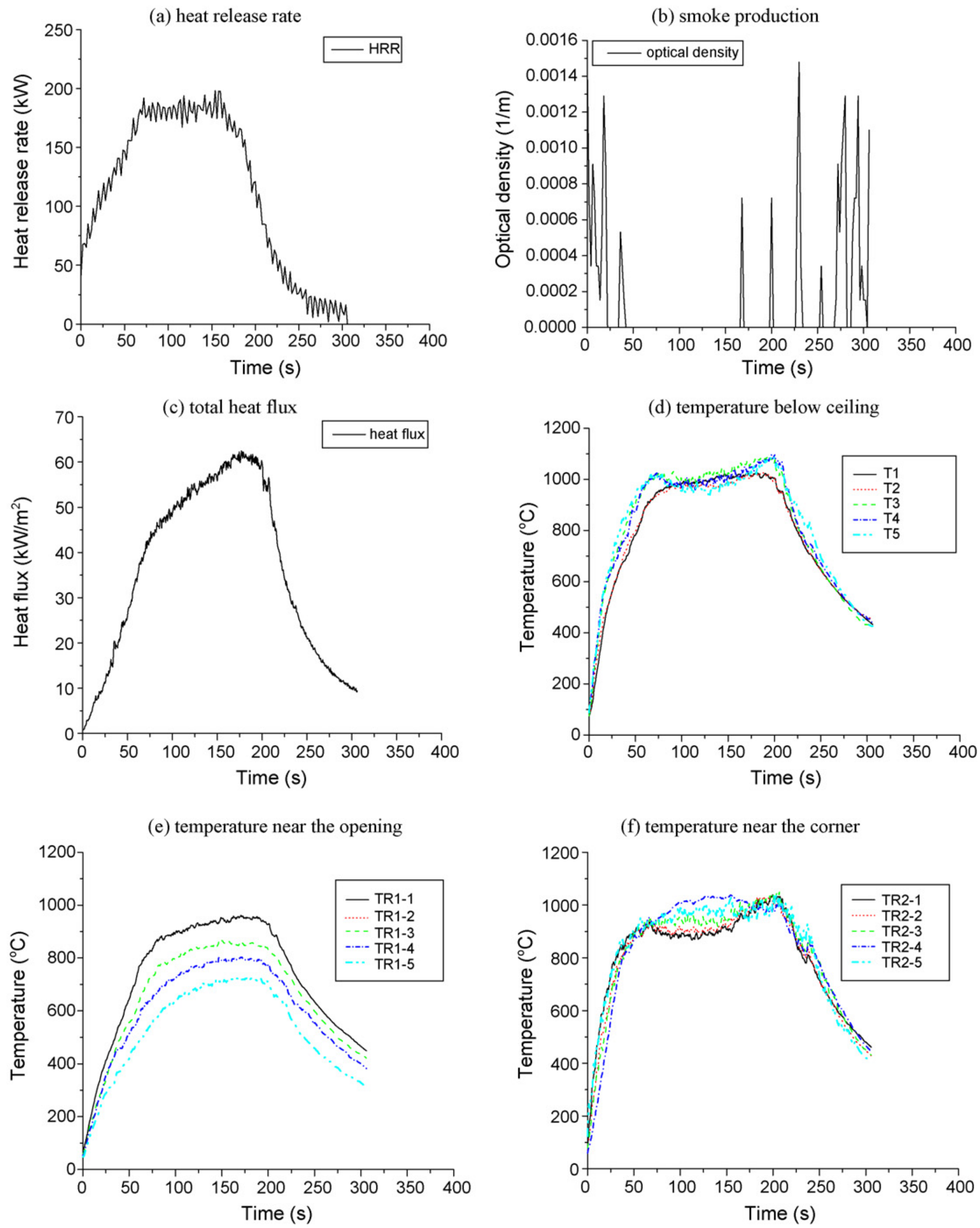

Fig. 4. (a–f) Time histories of HRR, smoke production, total heat flux on the floor, temperatures near the opening, near the corner and below the ceiling of a 1608 cm^2 methanol test.

2. Experimental

In this study, an experimental compartment, 1/3 the size of the ISO 9705 test chamber, was used to systematically examine the fuel sootiness effect. Fireproof cotton lined the inner walls and ceiling to reduce heat loss. Liquid pool fires using gasoline, *n*-hexane, *iso*-propanol and methanol (in order of decreasing sootiness [28]) were used as they have flames with low absorptivity and can be controlled by external combustion effect [29]. The liquid fuel was poured into circular pans with diameters of 100, 120, 150, 170, 190, 225 and 320 mm to produce fires with different HRRs and sootiness levels. The diameter range was determined for at least five flashover tests and one test without flashover. Table 1 shows the fuel areas generated by one fuel pan or the combination of two pans. Fig. 2 shows the positions of the fuel pans at the 3/4 position on the floor relative to opening in the opposing wall, giving F1, F2 and F3. The F1 indicates the position when only one fuel pan was used and F2 and F3 shows the positions when two pans were used. This experimental design facilitates determination of the lower bound values of important parameters. After ignition, this study determined the HRR, temperature below the ceiling, near the opening and near a corner, heat flux on the floor and time to flashover. The HRR was measured by an ISO 9705 Room test facility [12]: the test chamber was positioned under the hood of the ISO 9705 facility and the HRR was measured according to oxygen consumption principle [7]. Furthermore, Fig. 2 shows the positions of a total heat flux meter on the floor, five thermocouples 10 cm below the ceiling and two thermocouples trees

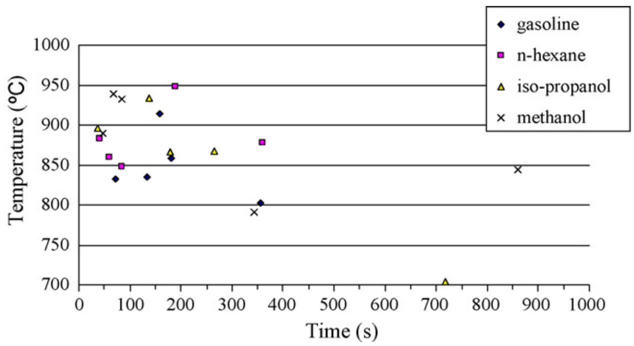

Fig. 5. Temperature below ceiling at flashover vs. time.

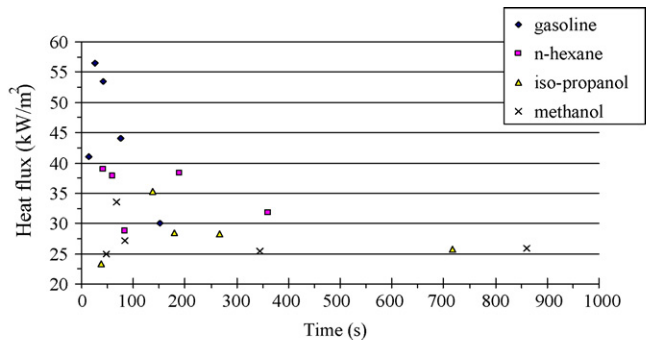

Fig. 6. Heat flux at floor at flashover vs. time.

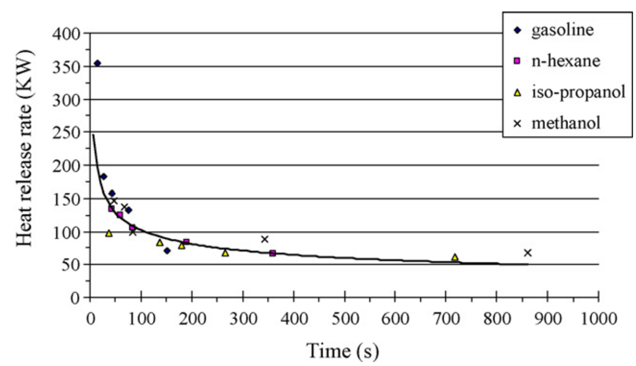

Fig. 7. HRR at flashover vs. time, giving a correlation of $\dot{Q} = 532.92t_{fo}^{-0.3466}$ ($R^2 = 0.77$).

– one near the opening and one near a corner. One thermocouple tree contains five thermocouples placed at 100-mm intervals from the ceiling to the floor. The thermocouple located the highest was designed to measure the temperature of the hot smoky layer and located at 100 mm below the ceiling. The readings of the thermocouple were more representative to the smoky layer temperature rather than those at 10 mm below the ceiling designed by Hägglund et al. [15]. The position 10 mm below the ceiling is too close to the ceiling and some heat actually conducts to the ceiling. The thickness of smoky layer exiting from the test chamber was observed by eye. Flashover was defined by flames exiting the opening.

3. Results and discussion

Figs. 3(a)–(f) and 4(a)–(f) show the time histories of the HRR, smoke production, total heat flux, temperature below the ceiling, temperature near the opening and temperature near a corner in the burning tests using 397 cm^2 gasoline and 1608 cm^2 methanol, respectively. The fuel areas were generated by combinations of the pans described in Section 2. The two datasets are from tests in which fuel sootiness was highest and lowest and almost identical times to flashover onset (44 and 46 s) and corresponding HRRs at flashover (154 and 150 kW). The gasoline fire produced significantly more smoke than the methanol fire. Total heat flux on the floor was also markedly higher for the gasoline fire. The temperature at T3 (Fig. 2) was highest, while that at T1 and T2 were lowest as they were relatively farther from the fire source. At flashover, the thickness of smoke layer exiting the opening was 43 cm for the gasoline fire and 48 cm for the methanol fire. Thus, the determined temperatures at TR1-1–TR1-3 correspond to the hot, smoky layer. The vertical temperature distribution of this smoky layer near the opening at flashover was 600–410 °C downwards for the gasoline fire (TR1-1–TR1-3 in Fig. 3(e)) and 630–540 °C for the methanol fire (TR1-1–TR1-3 in Fig. 4(e)). The determined temperature distributions of this smoky layer near a corner at flashover was from 750 to 600 °C downwards for the gasoline fire (TR1-1–TR1-3 in Fig. 3(f)) and 850–830 °C for the methanol fire (TR1-1–TR1-3 in Fig. 4(f)). The temperature of the smoky layer near a corner was higher than that near the opening. The lower temperatures near the opening were caused by mixing with fresh air.

3.1. The effect of fuel sootiness on temperature, heat flux and HRR at flashover

Figs. 5–7 present time histories for temperature, heat flux and HRR at flashover for all fires. Table 1 shows experimental data for time to flashover and the tests without flashover. Ceiling temperature of 703.9 °C, floor heat flux of 25.7 kW/m^2 and HRR of 62 kW, lower bound values of the parameters, are needed for flashover. Additionally, the effect of fuel sootiness on temperature is not significant as heat fluxes on the floor are generally high for sooty fuels. Furthermore, a relationship between HRR at flashover and time to flashover exists, yielding $\dot{Q} = 532.92t_{fo}^{-0.3466}$ ($R^2 = 0.7743$) (Fig. 7). This correlation can be regarded as the characteristic correlation for flashover in the experimental compartment. An intersection point in a diagram including this characteristic correlation and the HRR in this experimental compartment indicates an onset of flashover and corresponding time to flashover.

3.2. The effects of fuel sootiness

The characteristic correlation ($\dot{Q} = 532.92t_{fo}^{-0.3466}$) is fuel independent, even though total heat fluxes on the floor at flashover were clearly high for sooty fires (Fig. 7). Previous theoretical and numerical analyses all noted the importance of the heat feedback to a fuel [9,23,25], however, the effect of this feedback, strongly determined by fuel sootiness, was insignificant in both the HRR needed for flashover and time to flashover in this experimental study. Inconsistency seems to exist.

Further quantitative information is warranted to evaluate the effects of radiation on flashover. Two fires of the 397 cm^2 gasoline and 1608 cm^2 methanol fires are analyzed here as their fuel sootiness is highest and lowest in this study. The radiation on the floor was 53.4 kW/m^2 for the gasoline fire and 24.9 kW/m^2 for the methanol fire. Due to the very little smoke produced by the methanol fire (Fig. 4(b)), the radiation back to the methanol fuel during the fire was primarily from hot walls and the ceiling. However, time to flashover (44 s for the gasoline fire and 46 s for the methanol fire) and the corresponding HRR at flashover (154 kW for the gasoline fire and 150 kW for the methanol fire) were almost identical. The radiating heat feedback from the hot gas layer did not have a significant role in the times to flashover and the HRRs at flashover; otherwise, flashover will not occur with methanol fires.

An explanation is provided here. The burning of sootier fuels performed more radiation back to fuels and enhanced the generation of volatiles of the fuels. The HRR of the burning was consequently increased. Fuel sootiness obviously plays a role in the onset of flashover for sootier fuels. However, the effect of fuel sootiness was not seen in the fuel-independent characteristic correlation ($\dot{Q} = 532.92t_{fo}^{-0.3466}$) because the fuel sootiness effect was included in and demonstrated by the resultant HRR at flashover ($\dot{Q}$). As to fuels with very low degree of sootiness such as methanol in this study, the sootiness effect was relatively weak. However, the radiation from the smoky layer in the compartment was not the only source generating heat back to a fuel bed. Walls, ceiling and any fire source can also transfer heat back to the fuel. Therefore, a better description of the role of sootiness is that the fuel sootiness can play but not always play an important role in the onset of flashover. The fuel sootiness effect is important for sootier fuels. The HRR at flashover influenced by the combined effects from the smoky layer (related to the fuel sootiness) and other heat sources can be regarded better criterion for flashover ($\dot{Q} = 532.92t_{fo}^{-0.3466}$). Once a high HRR produces thermal instability that meets the fuel-independent flashover criterion $\dot{Q} = 532.92t_{fo}^{-0.3466}$, flashover occurs. The HRR is consequently the only most important parameter for flashover because other factors all contribute to the HRR. This experimental finding is in agreement with that obtained by Thomas [20].

4. Conclusion

The effects of fuel sootiness on flashover were determined experimentally. The following are the primary conclusions.

1. The effect of fuel sootiness on ceiling temperature at flashover was not obvious as heat fluxes at flashover were generally high for sooty fuels.
2. A clear trend exists in the relationship between HRR at flashover and time to flashover, yielding $\dot{Q} = 532.92t_{fo}^{-0.3466}$ ($R^2 = 0.7743$). This correlation can be considered the characteristic correlation for flashover in this compartment. The effect of fuel sootiness was not seen in the fuel-independent correlation because the fuel sootiness effect was included in and demonstrated by the resultant HRR at flashover ($\dot{Q}$).
3. A better statement describing the effect of fuel sootiness is provided. The fuel sootiness can play but not always play an important role in the onset of flashover. The fuel sootiness effect is important for sootier fuels. The HRR at flashover influenced by the combined effect from smoky layer (related to the fuel sootiness) and other heat sources can be regarded better criterion for flashover ($\dot{Q} = 532.92t_{fo}^{-0.3466}$).

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