Journal of Hazardous Materials 172 (2009) 763–772

Contents lists available at ScienceDirect

Journal of Hazardous Materials

journal homepage: www.elsevier.com/locate/jhazmat

Orientation effect on cone calorimeter test results to assess fire hazard of materials

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ARTICLE INFO

Article history:
Received 13 April 2009
Received in revised form 15 July 2009
Accepted 16 July 2009
Available online 23 July 2009

Keywords:
Fire hazard of materials
Cone calorimeter
Orientation

ABSTRACT

A cone calorimeter can provide material "reaction to fire" information for use in evaluating the fire hazard of materials. Two orientations can be selected, vertical or horizontal, depending on the geometry of materials in their final use. However, most fire models and material evaluation reports fail to consider the effects of the orientation and applied the horizontal case data. To assess the validity of using data with "horizontal" samples for further applications, a systematic experimental was performed using materials including PMMA, wooden products and polystyrene foams. Besides critical heat flux for ignition, other "reaction to fire" material properties were measured, including ignition time, ignition temperature, heat release rate history and mass loss rate when exposed to three heating irradiances, namely 15, 30 and 50 kW/m^2. For the horizontal orientation in comparison to the vertical orientation, the study data reveal relatively constant temperature distribution before ignition, lower critical heat flux for pilot ignition, shorter time to ignition, lower peak heat release rate, identical total heat release, longer burning time and almost identical combustion completeness for all the tested materials except polystyrene foams. Ignition temperature displaced no clear trend. Vertical orientation tests are consequently recommended for evaluating material fire performance.

1. Introduction

The cone calorimeter [1] is recognized worldwide as one of the most acceptable fire testing apparatus. In this test, the sample receives uniform irradiance from a conical heater, producing a heating environment that simulates the heating intensity of real fires. Two orientations – vertical or horizontal – of the conical heater and sample are selected based on the final geometry of the materials. Using an electric spark and other facilities, this apparatus can provide information on materials relevant to their fire performance for example critical heat flux for ignition, ignition time, heat release rate history, smoke and toxic gases productions, etc.

Since the introduction of cone calorimeter to fire safety community, many fire models and material evaluation reports have used the data for input or reference. However, surveying existing fire models [2–9] and material fire performance evaluation reports [10–23] (see Table 1) reveals that most do not consider orientation. Additionally, new Japanese and Australian Building Codes [24,25] employ the data conducted with horizontal samples exposed to 50 kW/m^2 irradiance in the cone calorimeter for surface lining material classification. The irradiance of 50 kW/m^2 is generally considered the heating intensity in a fully developed fire, but the validity of applying the horizontal sample requires further evaluation. In this investigation, analysing the behaviours of fires produced on horizontal and vertical samples in the cone calorimeter, a systematic experimental is performed to assess the difference of results carried out from tests employing the two orientations. Finally, the validity of using horizontal case data in material fire performance evaluation reports and building material combustibility classification regulations is discussed.

2. The heating environment in the cone calorimeter

Fig. 1 shows the schematic of dominant heat transfer and air entrainment mechanisms in the cone calorimeter for samples oriented horizontally and vertically. The radiative environments are very similar for the two orientations while the convective environments are very different. Babrauskas [26] described the convective environments from the perspective of ignition. "For a horizontal sample, air is entrained from all sides and relatively constant surface temperature is found across the face. For a vertical sample, a boundary layer is established, with the bulk of the flow being bottom-up." Consequently, in a cone calorimeter, the surface temperature of vertical samples is higher at the top than at the bottom. Additionally, a

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doi:10.1016/j.jhazmat.2009.07.061

Table 1
Models and evaluation reports using data of the cone calorimeter.

Models and evaluation reports	Fire scenario	Orientation of conical heater and sample
Tsai and Drysdale [2,3]	*Vertical* flame spread	Vertical
Grant and Drysdale [4]	*Vertical* flame spread	Vertical
Karlsson [5]	*Vertical* flame spread	Horizontal
Anderson and McKeever [6]	*Vertical* flame spread	Horizontal
Lattimer et al. [7]	*Vertical* flame spread	Horizontal
Quintiere and Lee [8]	*Vertical* flame spread	Horizontal
Hirschler [9]	Fire propagating from burning furniture to *vertical* finish material	Horizontal
Lefebvre et al. [10]	Burning on *vertical* polyurethane foam	Horizontal
Mouritz and Gardiner [11]	Fire on *vertical* polymer sandwich composites	Horizontal
Chow [12]	Burning on *vertical* polyurethane sandwich panel	Horizontal
Le Lay and Gutierrez [13]	Burning on *vertical* external warship surface	Horizontal
Elliot and Whiteley [14]	Burning on insulated wire	Horizontal
Salvador et al. [15]	Burning on cardboard and polyethylene	Horizontal
Price et al. [16]	Burning on foam/cotton fabric combination material	Horizontal
Rossi et al. [17]	Burning on polystyrene material	Horizontal
Mortaigne et al. [18]	Burning on piping material	Horizontal
Li [19]	Burning on polyvinyl chloride	Horizontal
Bourbigot et al. [20]	Burning on polybenzazole and p-aramidfibres	Horizontal
Chuang et al. [21]	Burning on plywood	Horizontal
Chuang et al. [22]	Burning on plywood	Horizontal
Tsai [23]	Substrate effect on five materials	Horizontal

roughly pyramidal volume of pyrolysis gases exists for the horizontal samples while a very thin sheet of pyrolysis products flowing upwards and along the surface exists the vertical orientation.

Additionally, Babrauskas [26] reported the time to ignition data for two round robin cone calorimeter tests. It takes 20% longer time to ignite vertical samples while Shield et al. [27] reported that this percentage increases to 40% in their report for cellulosic materials. This phenomenon can be explained observing the location of the spark ignitor and the shape of pyrolysate streams which are igniting. Around the ignitor, a flammable mixture is easily established in the horizontal orientation.

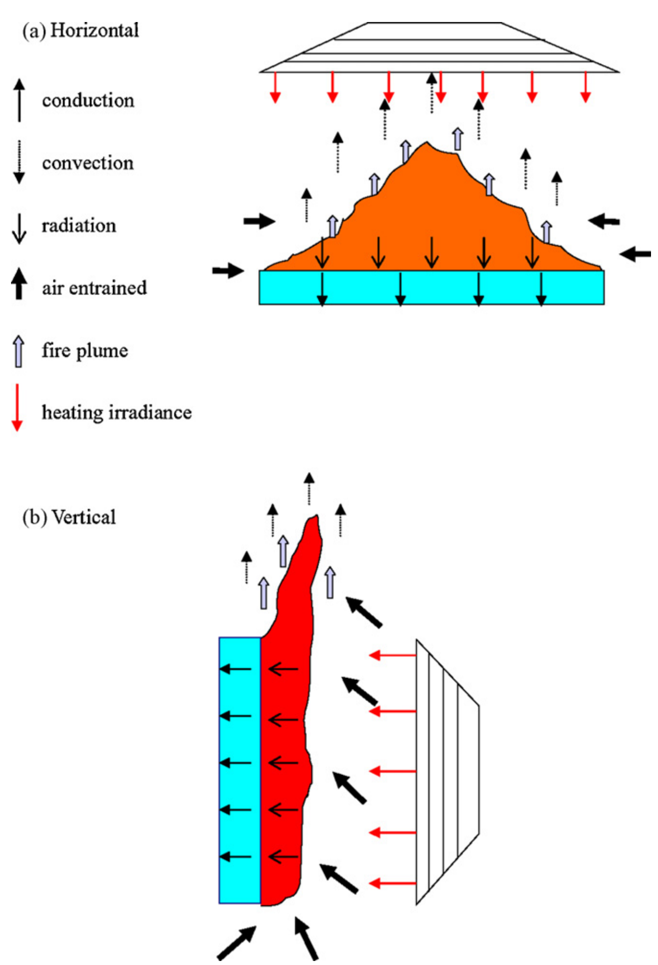

Fig. 1. The dominant heat transfer and air entrainment mechanism in cone calorimeter tests with samples oriented horizontally and vertically.

Based on the above analyses, clearly that the thermal environment, dominate heat transfer mode, air entrainment and the fire plume direction associated with these two configurations are very different. Therefore, before using data from the cone calorimeter, it is necessary to consider the testing environments. This study focuses on analyzing the effect using different heater and sample geometries. This clarification helps enhance the validity of evaluations of material fire performance.

3. Experimental

3.1. Experimental design

Seven different substances of materials including charring, non-charring and foam materials were used to assess the effect of orientation of the test results in the cone calorimeter. Table 2 lists their compositions, thicknesses and densities.

Measurements made in this study included critical heat flux for pilot ignition, surface temperature history, time to ignition, heat release rate history, burning time and mass loss rate under specific heating irradiances. The critical heat flux for ignition is determined by the lowest heat flux below which no ignition occurs after 15 min of sample exposure to heating irradiance. Additionally, the "reaction to fire" properties were measured under specific irradiances of 15, 30 and 50 kW/m^2, respectively. The 15 kW/m^2 irradiance corre-

Table 2
Thickness and density of testing materials.

Material index	Material	Thickness (mm)	Density (g/cm^3)
1	FR plywood	3	0.52
2	Plywood	5	0.64
3	Wood fiberboard	6	0.70
4	Wood fiber/cement board	6	1.35
5	PMMA	6	1.17
6	Polystyrene foam (A)	10	0.05
7	Polystyrene foam (B)	20	0.05

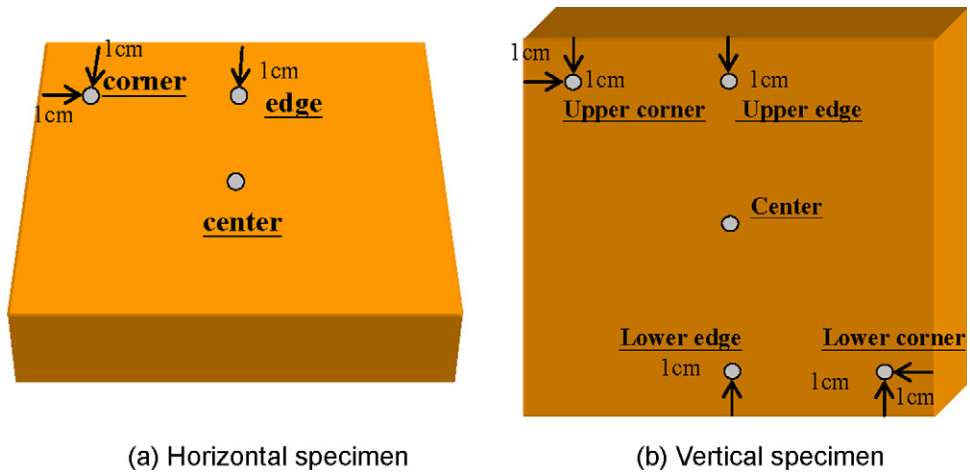

Fig. 2. The positions of thermocouples for measuring surface temperature.

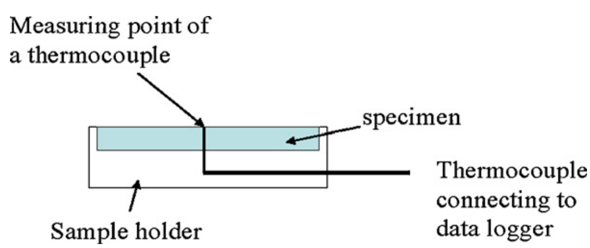

Fig. 3. The schematic of setting up thermocouples across a sample to measure surface temperature.

sponds to the early stage of a fire, while the heating intensities of 30 and 50 kW/m^2 simulate the fire scenarios during the growth and fully developed periods. The temperature history on the sample surface was investigated at representative positions shown in Fig. 2 and recorded using K-type thermocouples. Fig. 3 schematically depicts the thermocouple set up. Additionally, the mass loss rate was measured by a load cell. The ignition temperature was thus determined to be the corresponding surface center temperature upon starting a sustained flame. At that moment, the corresponding time to ignition was also carried out. Furthermore, the heat release rate history was measured via the oxygen consumption method and recorded automatically by the cone calorimeter.

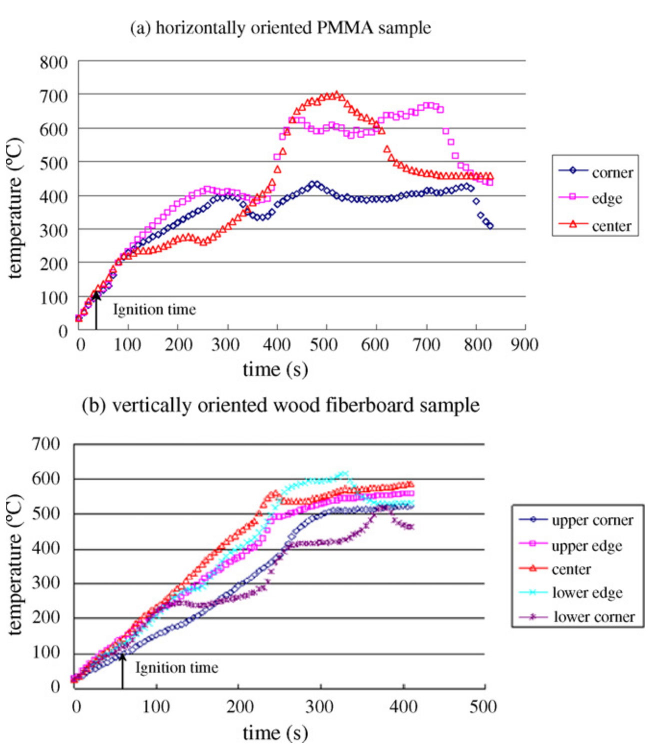

Fig. 4. The surface temperature histories of samples at 30 kW/m^2 irradiance. (a) Horizontally oriented PMMA sample. (b) Vertically oriented wood fiberboard sample.

3.2. Experimental results and discussion

Measurements made in this study included critical heat flux for ignition, ignition time, ignition temperature, heat release rate history, and mass loss rate, respectively. The data reported in this study are the average of three tests and are discussed below except for the data from polystyrene foam tests due to deformation during the tests. The repeatability of those polystyrene foam data is not high and the data are for reference only.

3.2.1. Surface temperature distribution

The surface temperature distributions including both the horizontal and vertical orientations were analyzed using data from three or five positions. A typical profile for horizontal samples is taken from the PMMA sample at 30 kW/m^2 irradiance (see Fig. 4a) while for vertical samples (see Fig. 4b) it is taken from wood fiberboard at 30 kW/m^2 irradiance. For all horizontal samples, before

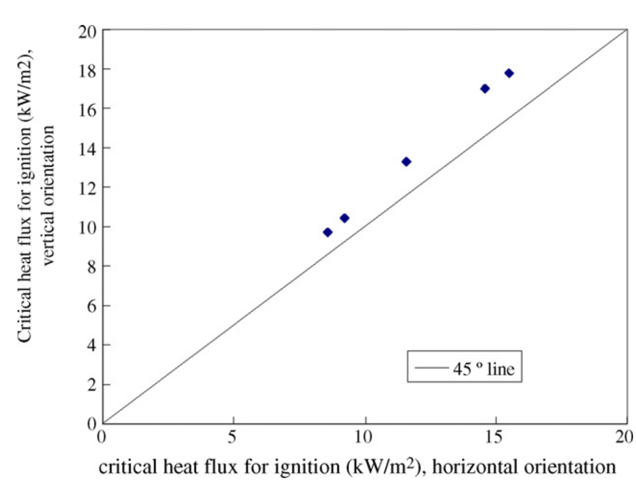

Fig. 5. The relation between critical heat fluxes for ignition in the horizontal and vertical orientation.

Table 3
Experimental, theoretical critical heat fluxes and TRP for pilot ignition.

Material index	Experimental critical heat flux for ignition (kW/m^2)		Experimental critical heat flux for ignition (kW/m^2)		TRP (W^2 s$^{0.5}$/m^2)	
	H	*V*	*H*	*V*	*H*	*V*
1	15.5 ± 1.3	17.8 ± 2.7	−2.2	5.6	203.0	205.2
2	11.6 ± 0.8	13.3 ± 1.1	4.7	9.3	205.7	209.0
3	8.6 ± 1.0	9.7 ± 1.5	2.8	2.6	235.1	256.5
4	14.6 ± 1.9	17.0 ± 3.2	−28.7	−39.2	1026.1	1254.1
5	9.2 ± 0.7	10.4 ± 0.6	1.0	1.4	250.8	268.7
6	14.5 ± 2.4	18.0 ± 3.7*	18.0	22.0	87.5	105.5
7	7.2 ± 1.2	17.4 ± 2.6	−66.8	−84.0	108.5	122.7

* These tests were conducted with grid on sample surfaces to prevent falling due to deformation.

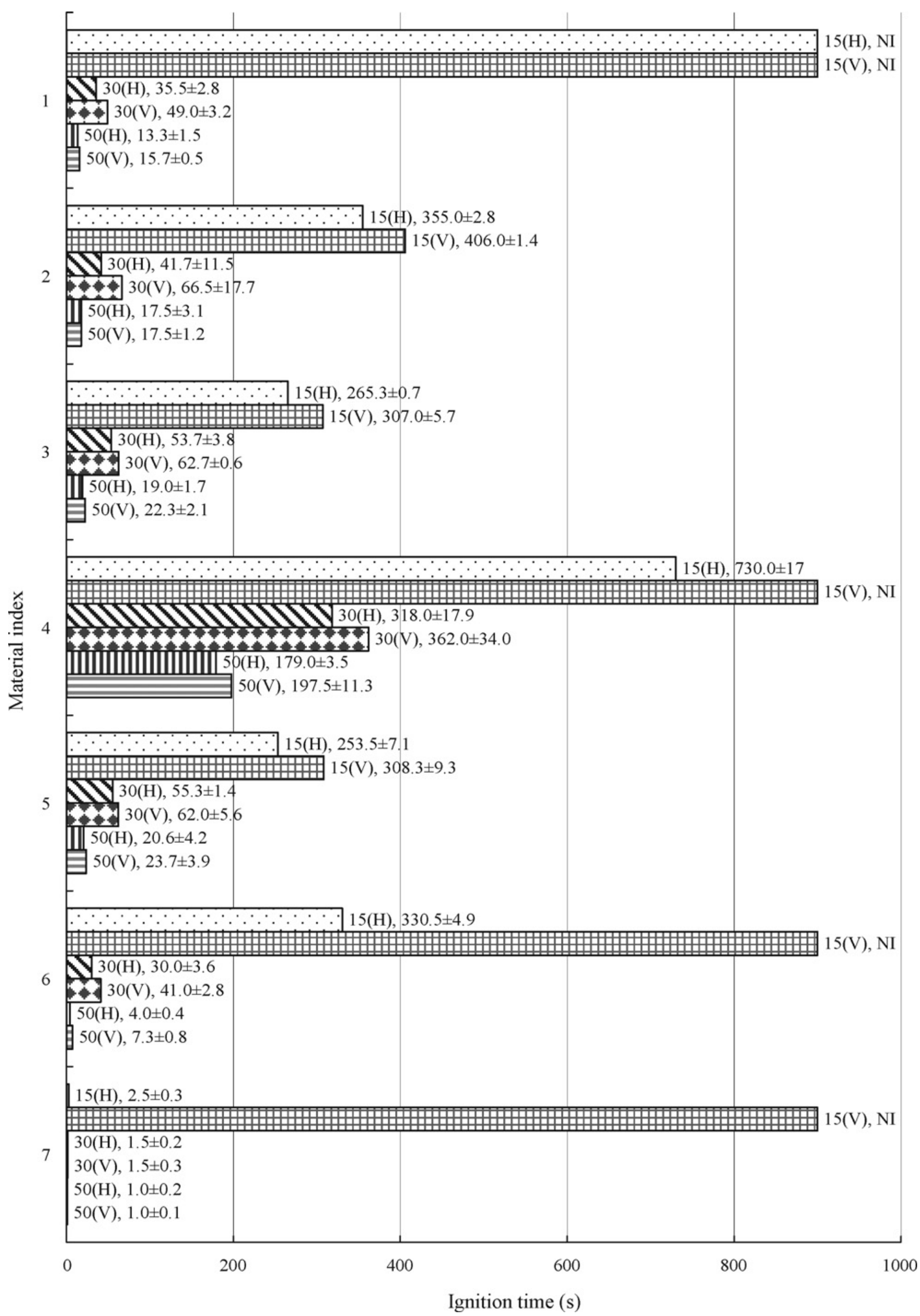

Fig. 6. Ignition time of materials exposed to three irradiances. The ignition time of 900 s represents "no-ignition" (NI).

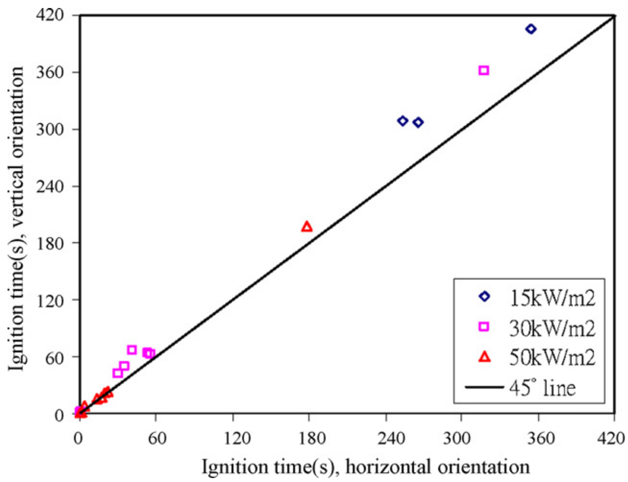

Fig. 7. The relation between ignition times in the horizontal $t_{ig}(H)$ and vertical orientation. $t_{ig}(V)$.

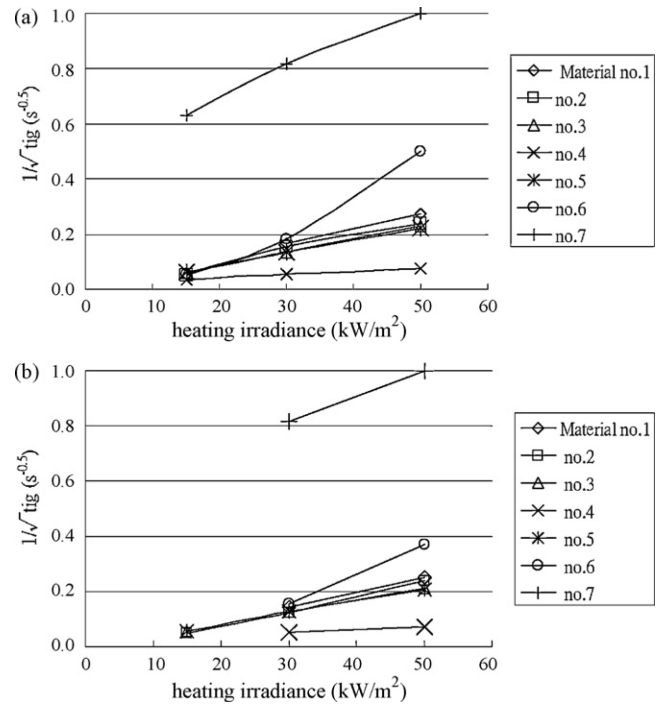

Fig. 8. (a) The plots of $1/\sqrt{t_{ig}}$, vs. $\dot{Q}''_R$ for horizontally oriented samples. (b) The plots of $1/\sqrt{t_{ig}}$, vs. $\dot{Q}''_R$ for vertically oriented samples.

ignition the distribution is uniform. However, with the vertical orientation, the temperature was highest at the "center" position, followed by "upper edge" and "lower edge". Notably, the temperatures were lower around the corners (upper and lower). This former observation is consistent with the conclusion of Babrauskas [26] but the latter is not. On the other hand, after ignition, the temperature distributions were not uniform and no trend could be discerned for the horizontal and vertical samples.

3.2.2. Critical heat flux for pilot ignition

Table 3 lists the measured critical heat fluxes for pilot ignition $\dot{q}''_{cr}$ of the tested materials. The materials are numbered as listed in Table 2. The theoretical critical heat flux and TRP (thermal response parameter, [26]) are also demonstrated and discussed in Section 3.2.3. Clearly, the heat flux for the vertical orientation is averagely 15% higher than that for the horizontal orientation (Fig. 5, Eq. (1), $R^2 = 0.998$). This is caused primarily by the effect of concurrent direction of entrained air and pyrolysis gas flow for the vertically oriented samples, which significantly dilutes the flammable vapors. Therefore, to achieve enough concentration of flammable vapors for ignition, the critical heat flux for pilot ignition for vertical samples is higher.

$$\dot{q}''_{cr}(V) = 1.15\dot{q}''_{cr}(H) \tag{1}$$

3.2.3. Ignition time

Fig. 6 shows the ignition time of the materials t_{ig} (horizontal and vertical samples) exposed to the 15, 30 and 50 kW/m^2 irradiances. Notably, ignition times were longer for materials exposed to lower irradiance. Additionally, the ignition times for vertical samples were 16% longer than for horizontal samples (Fig. 7), giving

$$t_{ig}(V) = 1.16t_{ig}(H) \tag{2}$$

where $t_{ig}(H)$ and $t_{ig}(V)$ denote the times to ignition for the horizontal and vertical orientations ($R^2 = 0.997$). This percentage is consistent with the analysis of Babrauskas (20%) [26], but lower than that derived by Shield et al. [27].

The ignition time for thermally thick materials is related to heating irradiance $\dot{Q}''_R$ indicated in Eq. (3). Fig. 8a and b plot $1/\sqrt{t_{ig}}$ vs. $\dot{Q}''_R$ for the tested materials.

$$t_{ig} = \frac{\pi}{4}k\rho c\frac{(T_{ig} - T_o)^2}{\dot{Q}''_{R^2}} \tag{3}$$

where $k\rho c$ denotes thermal inertia, T_{ig} represents ignition temperature, and T_o is ambient temperature.

The theoretical critical heat flux for pilot ignition of a material can be estimated via linear extrapolations of the plots. Delichatsios et al. [28] reported a 70% reduction of true values. Considering this reduction, Table 3 lists the theoretical values. Some estimated values are less than zero and thus unreasonable. Even with these positive values, the theoretical critical heat flux is generally much lower than the experimental flux. This phenomenon may be due to the definition of no-ignition as the failure of flames to appear within 900 s. The critical heat flux for pilot ignition would be lower if the time period for the definition of non-ignition was extended. Additionally, the "thermal response parameter" (TRP) introduced by Tewarson [29] (see Eq. (4)) is suggested to be a means of assessing the ignition resistance of materials and can be derived from the linear part of the $1/\sqrt{t_{ig}}$ vs. $\dot{Q}''_R$ diagram. Table 3 lists the TRP values. Clearly, the TRP values for the vertically oriented samples are higher than those for the horizontally oriented samples.

$$\text{TRP} = (T_{ig} - T_o)\sqrt{k\rho c} \tag{4}$$

3.2.4. Ignition temperature

This study measures surface temperature history and the ignition temperature is determined as the corresponding temperature at the 'center' of a sample where an electrical spark was prepared upon the appearance of a sustained flame. Fig. 9 illustrates that the ignition temperature depends not only on the material properties but also strongly on the experimental conditions (irradiance, sample orientation) as concluded by Fangrat et al. [30]. Their investigation [30] additionally noticed that the average values obtained for the vertical orientation are generally much higher than those for horizontal samples and provided a probable reason for the different mechanism of ignition resulting from different configurations. However, this study failed to identify any clear trend in the influences of orientation while the temperature at ignition increased with lower irradiance.

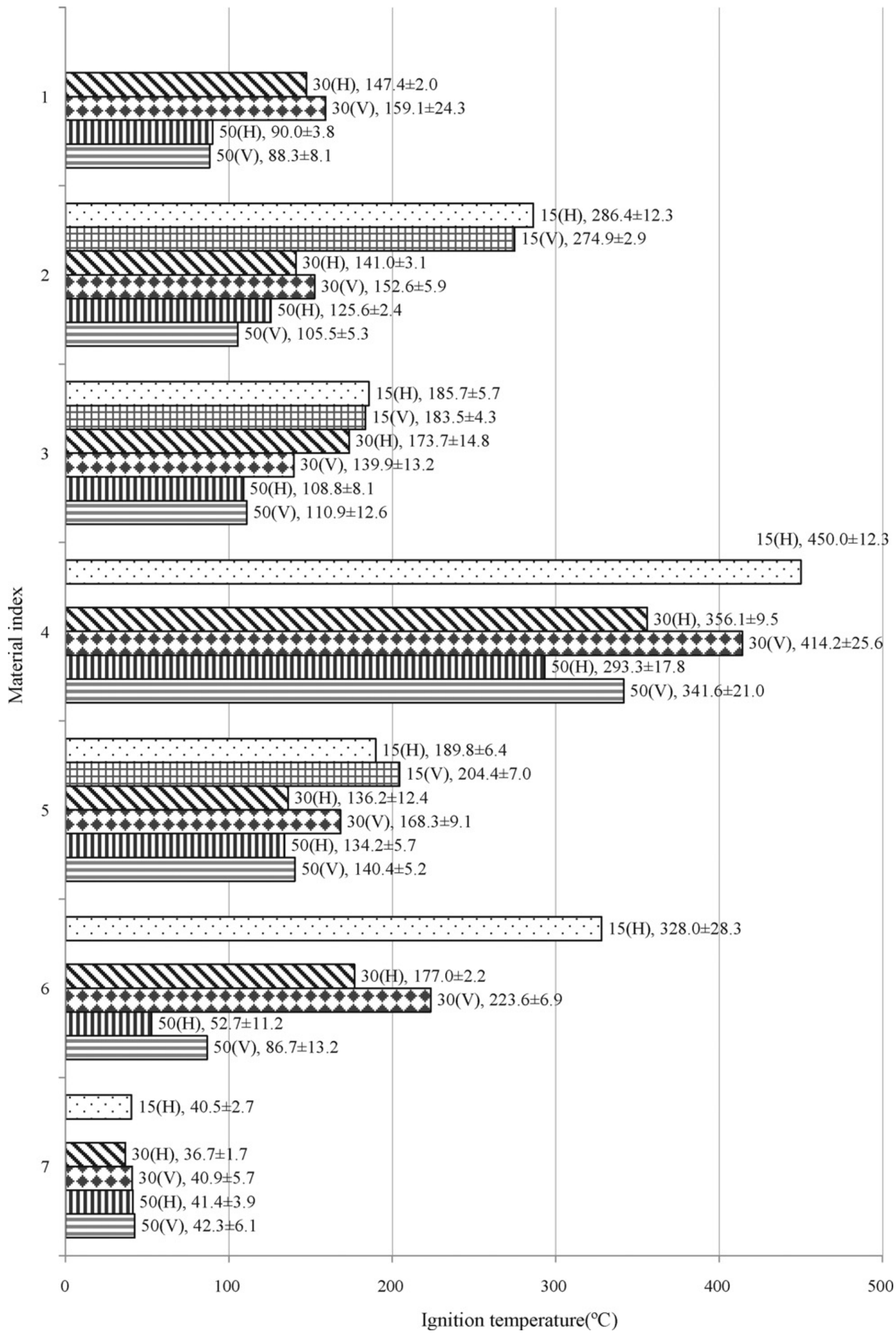

Fig. 9. Ignition temperature of materials exposed to three irradiances. The "blank" represents "no-ignition" (NI).

Ignition temperature is usually regarded as a material property and is defined as the temperature at which a sufficient concentration of flammable vapours has been produced. However, in a cone calorimeter, an enforced upward flow exists and dilutes the vapours along the surface of samples. Thus, the heat transfer (particularly convection) impacts the material ignition temperature.

3.2.5. Heat release rate

Fig. 10 shows the peak heat release rates per unit area (PHRR) of materials exposed to the three irradiances. The PHRR present increases with irradiance set. Additionally, PHRR is 10% higher for vertical samples (Fig. 11, Eq. (5), $R^2 = 0.966$). Furthermore, Fig. 12 shows the total heat release per unit area (THR) of materials exposed to the three irradiances. The THR values are almost identical under different conditions (irradiance, orientation).

$$\mathrm{PHRR}(V) = 1.10\mathrm{PHRR}(H) \tag{5}$$

3.2.6. Burning time

Fig. 13 demonstrates the burning time (testing time minus ignition) for the two orientation and three irradiances and Fig. 14 compares the differences of the data from tests with vertical and horizontal samples. For the vertical samples, the burning time gen-

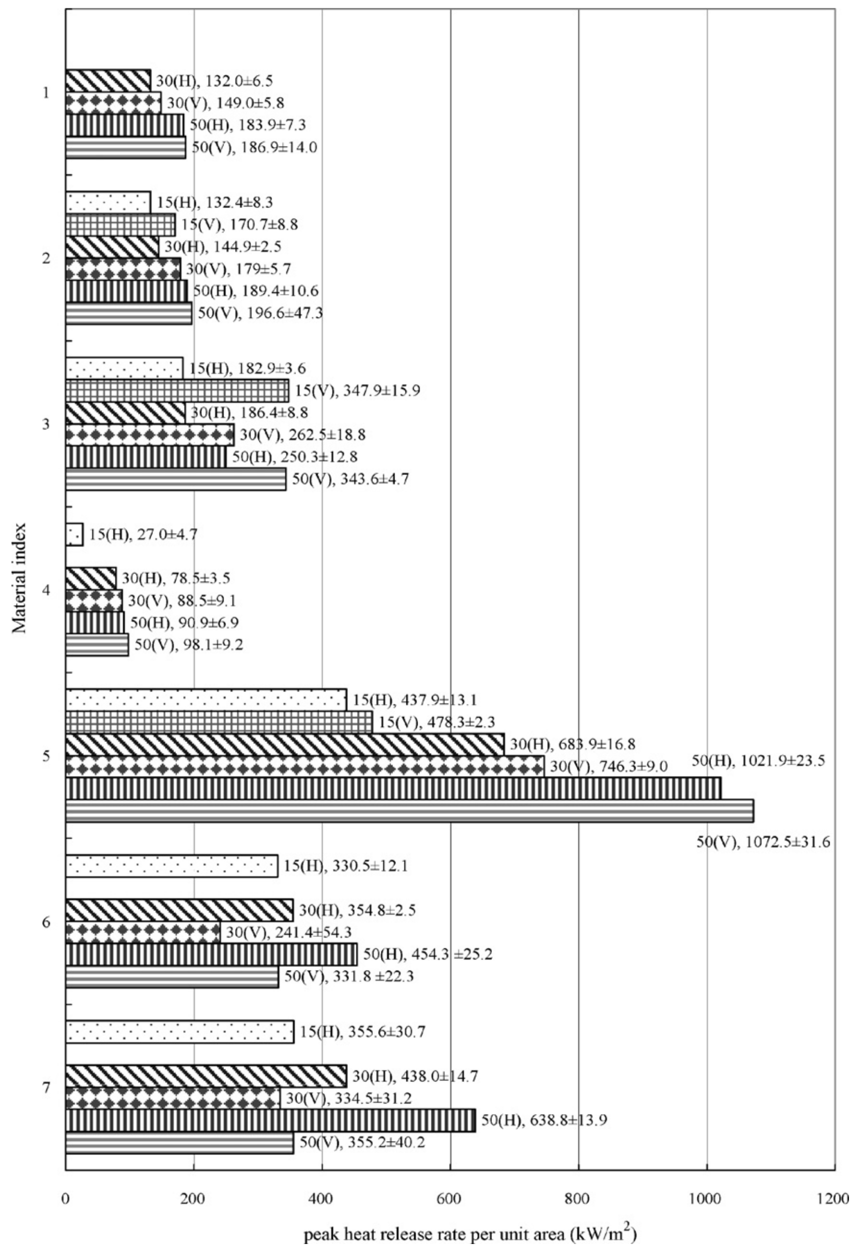

Fig. 10. Peak heat release rates (PHRRs) per unit area of materials exposed to three irradiances. The "blank" represents "no-ignition" (NI).

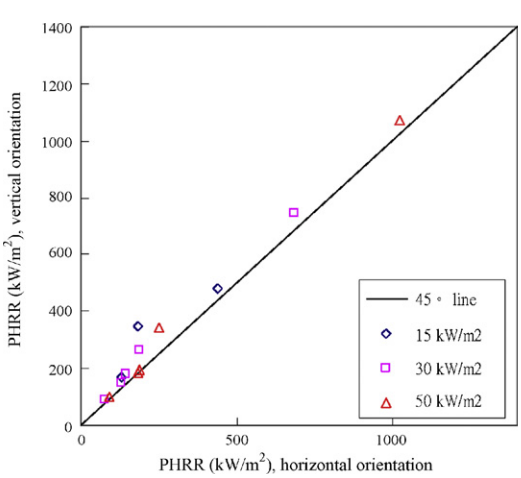

Fig. 11. The relation between PHRR in the horizontal and vertical orientation.

erally is 18% less (Eq. (7), $R^2 = 0.904$).

$$t_b(V) = 0.82 t_b(H) \quad (6)$$

3.2.7. Combustion completeness

This study did not measure the CO and CO_2 concentrations but the combustion completeness (χ) can be derived based on mass loss rate ($\dot{m}$), heat of combustion (ΔH_c) and resultant heat release rate (HRR), respectively.

$$\chi = \frac{\text{HRR}}{\dot{m}\Delta H_c} \quad (7)$$

Fig. 15 illustrates a typical combustion completeness (χ) history against the time after ignition as determined by a horizontal PMMA test at 15 kW/m^2 radiant heat flux. The heat of combustion (ΔH_c) of PMMA is assumed to be 24.89 kJ/g [29]. Just after ignition, an unsteady period occurred, followed by a relatively steady period after which the completeness gradually reduced until the end of the test. Some values are greater than 1, owing to data re-production. On

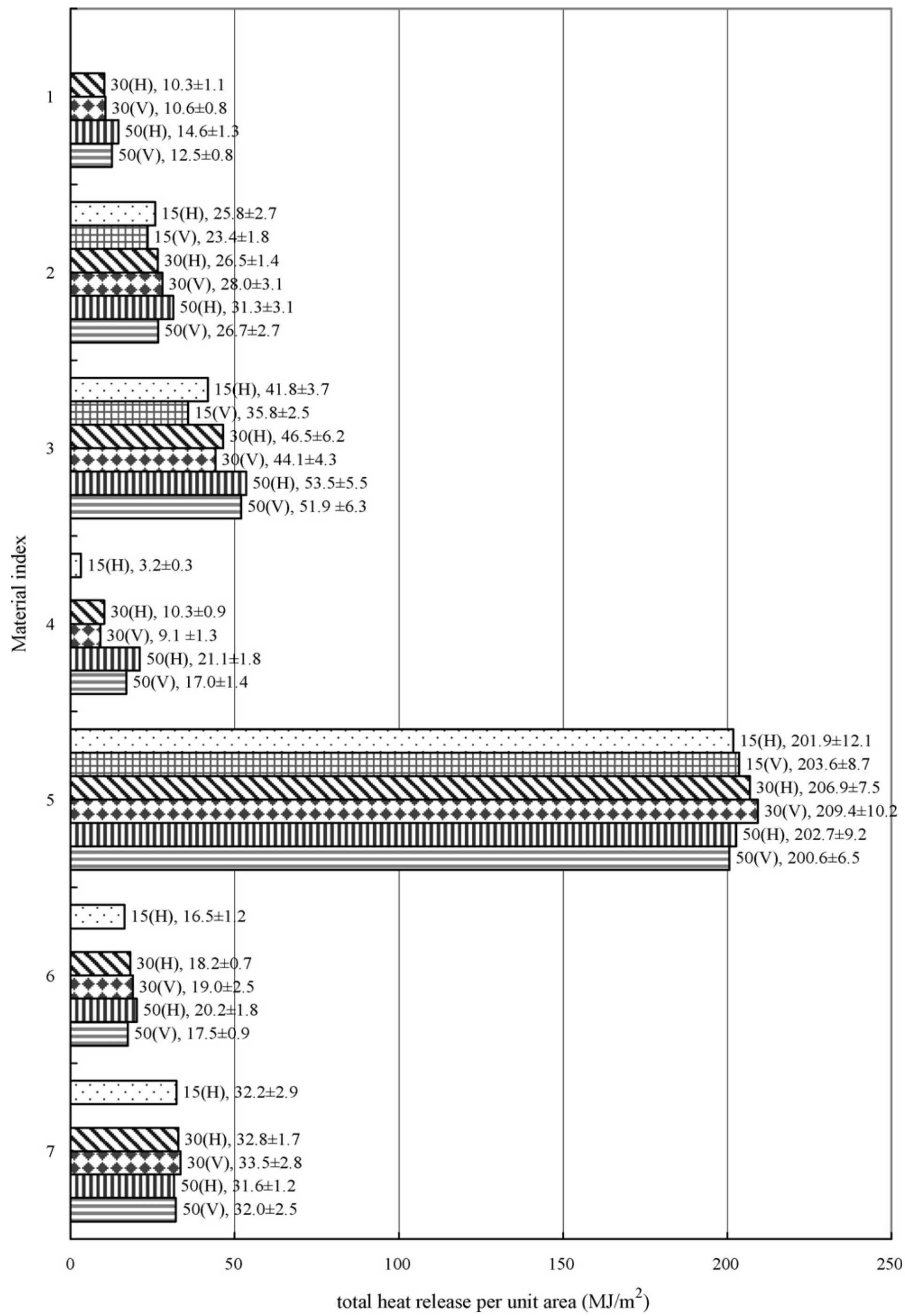

Fig. 12. Total heat release (THR) per unit area of materials exposed to three irradiances. The "blank" represents "no-ignition" (NI).

average, the value of χ in this test is 0.73. Additionally, investigating the values χ in other PMMA tests at 15, 30 and 50 kW/m^2 irradiances reveals that they are all between 0.69 and 0.73 and that no trend exists for irradiance level. This conclusion is consistent with the observation of Tewarson [29] using FM Flammability Apparatus, yielding 0.71 at external heat fluxes of 39.7 and 52.4 kW/m^2. Irradiance level and orientation do not affect the value of combustion completeness (χ) in the cone calorimeter.

3.2.8. Regulation use

The data of PHRR and THR at 50 kW/m^2 irradiance for 5, 10 or 20 min periods are used in Japan and Taiwan to evaluate the fire performance of building materials. Based on the comparison of the data carried out in this work, the PHRR values are generally higher for vertical samples, while the THR values are almost identical for vertical and horizontal samples. The difference of PHRR value reaches 37.25% for material no.3 at 50 kW/m^2 irradiance. Therefore, the worst case is generally the vertical orientation and the application of the "vertical" data should be stricter. Actually, it seems more realistic to utilize vertical samples because most building materials (or interior finish materials) are constructed vertically. Flames on vertical materials spread faster and more hazardous than horizontal materials. Additionally, the melting behavior of a vertical sample should be observed if possible.

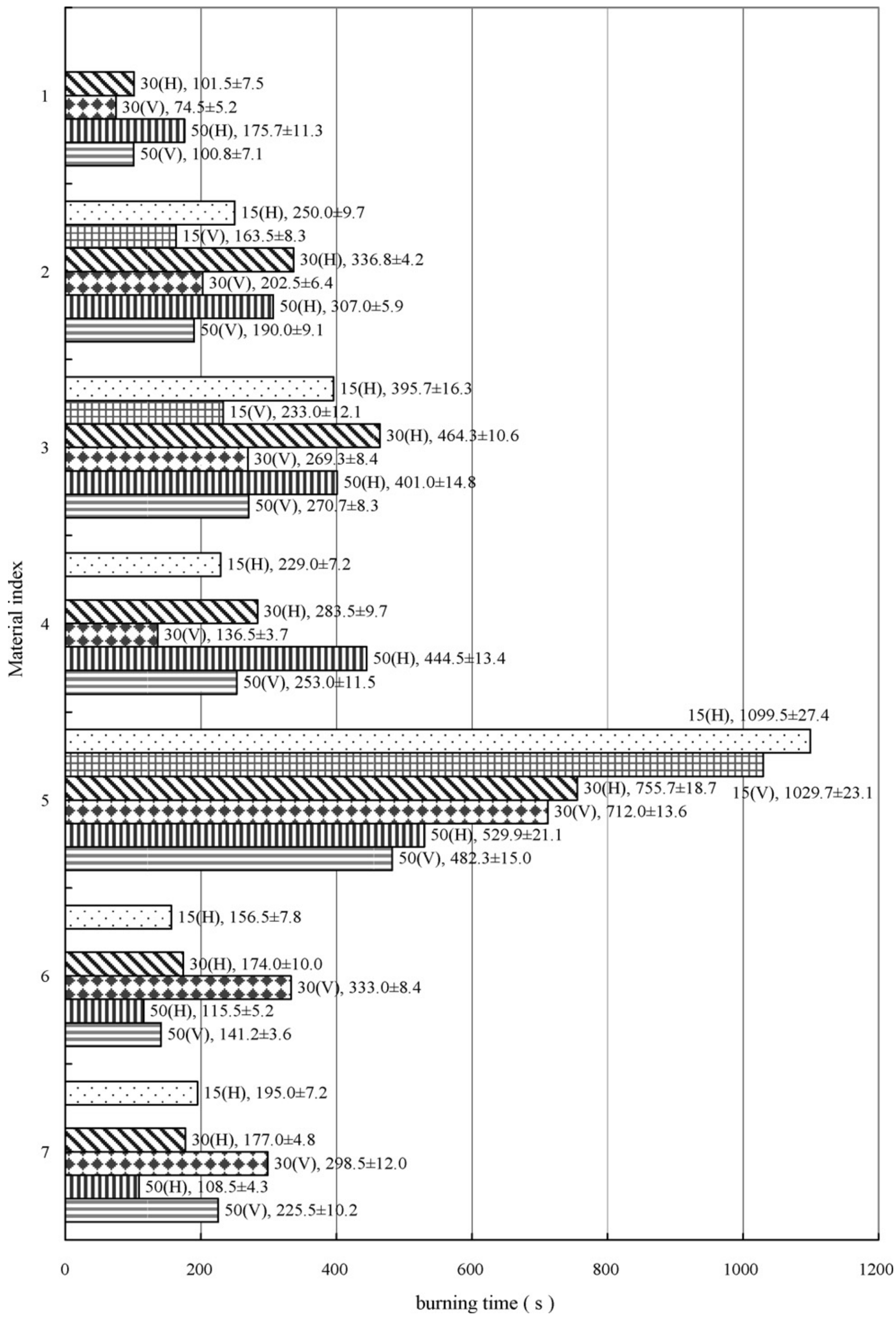

Fig. 13. Burning time of materials exposed to three irradiances. The “blank” represents “no-ignition” (NI).

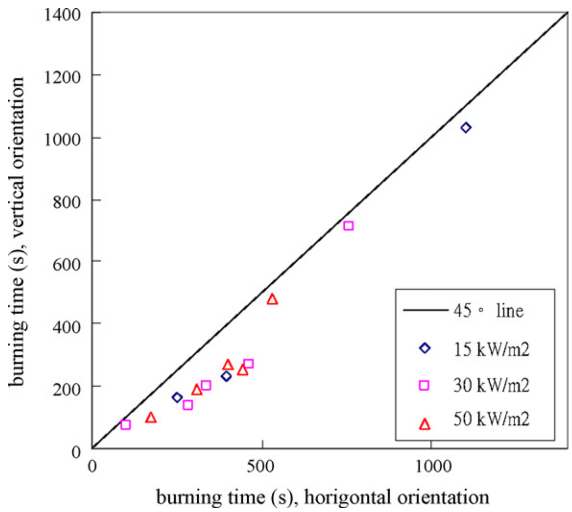

Fig. 14. The relation between burning times in the horizontal and vertical orientation.

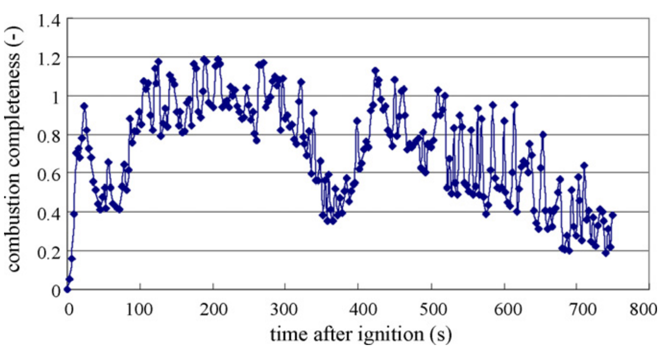

Fig. 15. The combustion completeness history of a PMMA sample at 15 kW/m^2 irradiance.

4. Conclusion

A systematic experimental study was performed to evaluate the effect of orientation on cone calorimeter data using seven materials including PMMA, wooden products and polystyrene foams. Besides critical heat flux for ignition, other "reaction to fire" properties of materials including ignition time, ignition temperature, heat release rate history and mass loss rate were measured when exposed to three heating irradiances, 15, 30 and 50 kW/m^2, respectively. The repeatability of the test data was high besides the polystyrene foam tests resulting from deformation during heating. The study data show that for horizontal orientation, there is a relatively constant temperature distribution before ignition, lower critical heat flux for pilot ignition, shorter time to ignition, lower peak heat release rate, identical total heat release, longer burning time and almost identical combustion completeness than for vertical orientation for all the tested materials. Additionally, no clear trend exists for ignition temperature. Furthermore, vertical orientation tests are recommended for material fire performance evaluation in regulation use because the worst case is generally the vertical orientation and the geometry of materials is usually vertical in their end use.

Acknowledgments

The author would like to thank Mr. Zhon-Chun Chen for conducting experiments and Mr. Shin-Chuan Huang for data analysis. In addition, financial support from National Science Council, TAIWAN (grant number: NSC 94-2212-E-327-010) is appreciated.

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