Flaming Combustion Characteristics of Wood-Based Materials

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ABSTRACT

This paper presents the results of an experimental investigation into the flaming combustion characteristics of wood-based materials. The present work was primarily motivated by the fact that combustible solids, particularly cellulosic materials, often constitute the bulk of fuels in many building fires. In order to achieve this task a number of small-scale experiments on samples of different wood species were performed using a cone calorimeter. In all cases the effects of controlling factors, such as the irradiance level, moisture content and the orientation of the sample were carefully examined. It was found that the experimental data are quite sensitive to these factors. In particular, the effect of the moisture content on the heat of combustion and heat release rate was found to be quite significant. The results of the experiments were also used to develop some useful correlations.

INTRODUCTION

When a solid object is exposed to fire heating it undergoes thermal degradation. The resulting pyrolysis reactions cause a mixture of volatile gases to rise and flow out of the solid object. Under certain conditions, these volatiles react with the oxygen in the boundary layer and undergo flaming combustion. Consequently, heat is released by the gas-phase combustion of volatile products. A part of this heat is transferred back to the solid object to continue the process. In the case of charring materials, such as wood, not all the original fuel becomes vapour, but some of it remains as a carbonaceous residual (char) which has a highly porous structure. When pyrolysis of such a material continues, the volatiles must pass through the char layer to reach the surface. This char layer is a good thermal insulator and can significantly alter the heat and mass transfer processes which occur in the solid matrix. Thus secondary reactions may occur in the volatiles as a result of their interaction with the hot char layer. As the char layer thickens, the heat flow into the solid and

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consequently the decomposition rate are reduced. The pyrolysis process continues until either all the volatiles are consumed or the heat flow into the material becomes negligible.

The entire process involves a number of complex chemical and physical phenomena which are currently understood in a gross fashion. These phenomena are greatly affected by a number of factors [1] which fall broadly into two categories, namely (a) external factors and (b) internal factors. Factors external to the solid fuel are environmental factors, such as the temperature and oxygen concentration of surrounding gases, as well as the magnitude and spectral content of the radiant heat flux. Internal factors are those related to the thermo-physical and thermo-chemical properties of the material, its moisture content and its geometrical parameters. Among these factors, the effect of moisture content is more significant for cellulosic materials like wood. The main reason is that these materials are hygroscopic and have a porous structure. As a result they can easily absorb water from the surrounding air. This in turn, changes the heat and mass transfer processes occurring during the flaming combustion period.

The main objective of the present work is to investigate the effects irradiance level, density, moisture content and orientation on the major flaming combustion characteristics of wood-based materials, such as the heat release rate (HRR) and the heat of combustion (HOC).

METHODS AND MATERIALS

In this study a cone calorimeter was utilised to perform the experiments. This instrument operates based on the concept of oxygen consumption calorimetry [2] and has been chosen as the standard bench-scale heat release rate apparatus by most of the research laboratories around the world. A full description of the technical features of this apparatus can be found elsewhere [3]. Briefly, the experimental procedure for each sample involved the following steps: (a) setting the radiant heater to the desired value; (b) exposing the sample to the radiant flux; (c) turning on the spark ignition system; (d) waiting for the appearance of a stable flame at the surface of the sample and then turning off the ignition system; (e) leaving the sample to burn freely until the flame dies out. A minimum of two runs were carried out for each material at each heat flux. If the runs were significantly different a third run was carried out.

The experiments performed for the present study can be subdivided into three series. The first series consists of oven-dry samples of four Australian wood species and two wood-based products, over a range of irradiance levels between 20 and 85 kW/m^2, in the horizontal orientation. The materials in the first series were chosen to investigate the effects of irradiance and density on HRR. Four different Australian wood species and two wood-based materials were used for the first series of tests. Table 1 gives more information about this series.

Material	Density (kg / m^3)	Thickness (mm)
Pacific maple	544	19, 42
Sugar pine	430	19
Radiata pine	465	19
Victoria ash	640	19
Particleboard	663	19, 22
Plywood	511	19

Table 1: Oven-dried materials used in the first series of tests

The second series of tests were designed to study the effect of moisture content on HRR and HOC. For this purpose the test samples of Pacific maple, Sugar pine, Radiata pine and Victorian ash were conditioned to the moisture content levels of 10%, 15%, 22% and 30% using the method outlined in an earlier work [4]. All specimens were tested at irradiance levels of 25 kW/m^2, 45 kW/m^2, 65 kW/m^2 and 85 kW/m^2 in the horizontal orientation.

The experiments of the last series were performed on oven-dry samples of Pacific maple and Radiata pine in the vertical orientation. The results were then compared with those obtained from the first series in order to quantify the effect of orientation on HRR.

RESULTS AND DISCUSSION

The standard results for a typical test in the cone calorimeter include up to 12 different properties for each test sample. The major results are: ignition time, mass loss (ML), total heat release, heat release rate (HRR), heat of combustion (HOC), carbon dioxide (kg/kg of ML), carbon monoxide (kg/kg of ML) and smoke specific extinction area (m^2/kg of ML). Properties are usually presented as time based graphs and tabulated results which include both peak and average values.

A typical set of tabulated results for a wood (Pacific maple) sample at an incident heat flux of 20 kW/m^2 is presented in Table 2. Average values are obtained for 1, 3, 5 and 10 minute periods after ignition. Early peak values are often difficult to obtain accurately because of the steep variation in the data around the peak value and the fact that the data acquisition system collects data at intervals of 3 to 5 seconds. Therefore, the 1 minute average is a more reliable representation of the early peak value.

Test Results:
Total mass loss = 74.11 g in 1355 s from ignition
Time to ignition (s) = 205
Energy to ignition (kJ/m^2) = 4107
Total heat generated (kJ) = 952

Averages & Peaks Over the Entire Test:
Average Heat of comb. was calculated between ignition & end of test. Other averages were calculated between 10% & 90% of total mass loss (e.g. between 100 s and 1160 s from ignition).

PARAMETER	*AVERAGE*	*PEAK*	*PEAK TIME FROM IGNITION*
Heat release rate (kW/m^2)	64.2	210.3	5
Effective heat of comb (MJ/kg)	12.8	17.0	1160
Mass loss rate (g/s)	0.05541	0.09450	1090
Sp. smoke ext. area (m^2/kg)	16.6	36.9	430
Carbon dioxide (kg/kg)	1.40	2.07	1160
Carbon monoxide (kg/kg)	0.0267	0.07	445

Averages During Successive Times (1, 3, 5, 10 min.) From Ignition:

	1 min	*3 min*	*5 min*	*10 min*
Heat release rate (kW/m^2)	129.3	86.3	73.7	59.3
Heat of comb (MJ/kg)	14.8	13.1	12.3	11.2
Mass loss rate (g/s)	0.08711	0.06589	0.05999	0.05318
Sp. smok. ext. area (m^2/kg)	38.7	17.4	11.4	12.0
Carbon dioxide (kg/kg)	1.62	1.48	1.42	1.30
Carbon monoxide (kg/kg)	0.0049	0.0084	0.0136	0.0312

Table 2: Experimental data for Pacific maple at an irradiance of 20 kW/m^2

ANALYSIS OF THE HEAT RELEASE DATA

For wood materials, the general shape of a typical HRR curve consists of a sharp peak soon after ignition. As the char layer gradually builds up, due to the low thermal conductivity of the char layer, the thermal resistance continuously increases, resulting in a decreasing rate of heat release after the first peak. For a sample with sufficient thickness, this decreasing trend continues until the HRR stabilises to a steady rate. However, for materials with finite thickness, a second peak appears near the end of the flaming combustion period. This peak is the result of a rapid rise in the bulk temperature of the remaining material. The second peak is not a property of the material and it is primarily dependent on the un-exposed face conditions. For instance, if the back face is not insulated the second peak will not be observed.

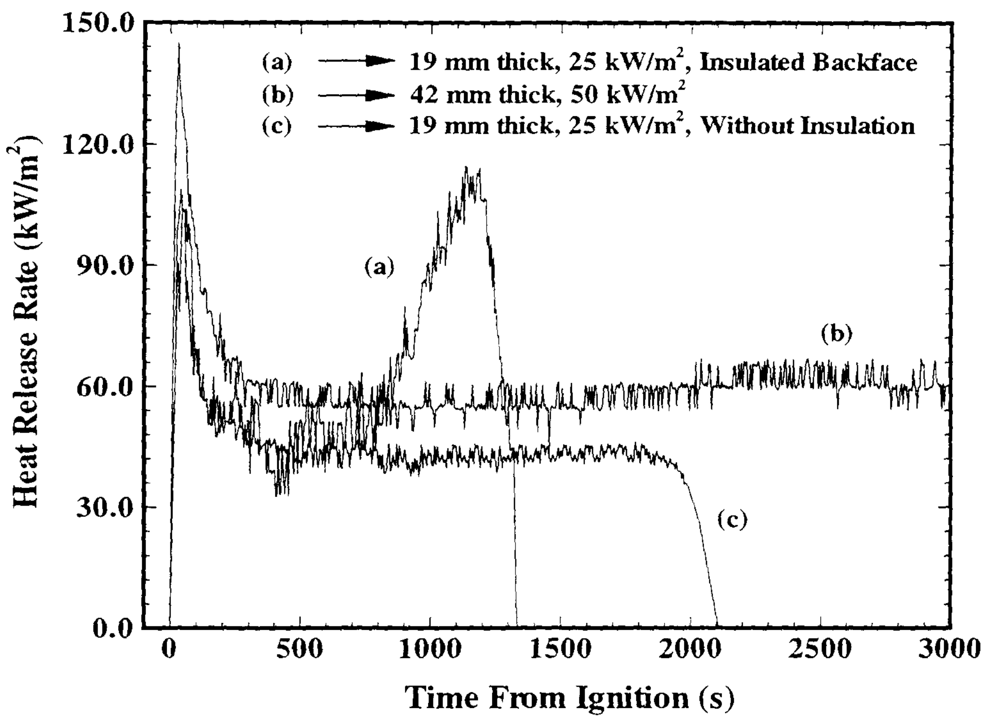

Figure 1: Heat release rate for 42 mm and 19 mm thick Pacific maple specimens.

Figure 1 illustrates the HRR curves for 42 mm and 19 mm thick Pacific maple specimens tested in the horizontal orientation at different levels of external heat flux. As this figure indicates, due to the effect of finite thickness, the 19 mm thick sample with an insulated backface shows the second peak even though it has been exposed to a lower level of irradiance compared with the 42 mm thick sample. However, without an insulated backface, the 19 mm thick sample behaves quite like the 42 mm thick sample.

Generally the part of the HRR curve around the first peak is more important than the region around the second peak, mainly because the initiation and growth of a typical room fire depend on the first peak of the HRR curve. However, as discussed before, it is difficult to quantify the first peak accurately. Therefore, in this study the 1 min and 5 min averages are used to characterise the region around the first peak.

In order to investigate the influence of irradiance on the rate of heat release, HRR can be plotted as a function of external heat flux. As shown in Figures 2 and 3, the average HRR increases linearly with the irradiance. For each material, the parameter of interest here is the slope of the linear regression fit through the appropriate set of data. However, it is possible to generalise the results and derive a single slope for all materials if all sets of data are combined together. Consequently, the following regression equations are obtained for 1 and 5 min average heat release rates ($HRR_{1\,min}$, $HRR_{5\,min}$) in the horizontal orientation:

$$HRR_{1\,\mathrm{min}} = 1.05 \times \dot{q}_e^{//} + 98 \qquad (kW/m^2) \qquad (1)$$

$$HRR_{5\,\mathrm{min}} = 1.41 \times \dot{q}_e^{//} + 39 \qquad (kW/m^2) \qquad (2)$$

where $\dot{q}_e^{//}$ is the external radiant heat flux. These relationships are quite similar to those reported by a number of other researchers [5, 6] and can be used for estimating the HRR of wood materials.

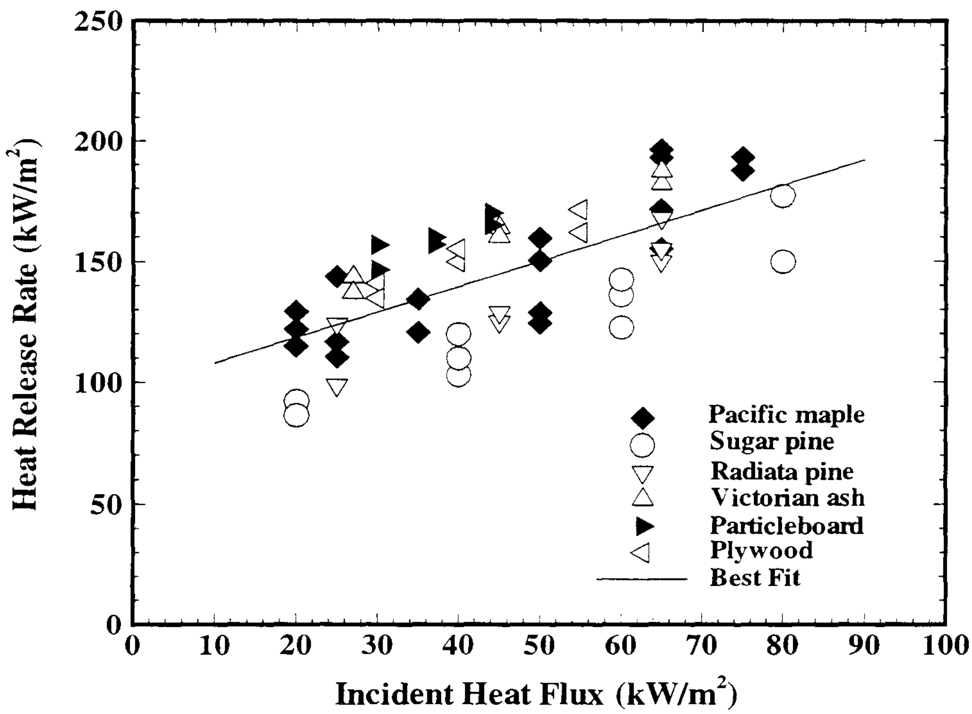

Figure 2: One-minute average HRR of six wood materials.

As Figures 2 and 3 indicate, the density has a significant effect on the HRR curve. Generally speaking, the greater the density the higher the heat release rate. In order to make a closer examination of this effect the experimental results have been plotted in Figure 4 as a function of oven-dry density. Although Figure 4 confirms the hypothesis presented here, due to scatter in the data, it is not possible to obtain an accurate estimation of the effect of density on HRR.

As mentioned before, the data obtained from the second series of experiments were used to study the effect of moisture content on HRR. It is obvious that the moisture content should act to reduce the HRR. However, in order to quantify this effect it is necessary to perform the experiments over wide ranges of the moisture content and external heat flux. For this reason, in this study, test samples of four different Australian species with moisture content levels between 0% to 30% were tested over a range of radiant heat fluxes between 25 kW/m^2 to 85 kW/m^2. A summary of the average heat release rates of Radiata pine specimens are shown in Figure 5, where the open and closed symbols represent $HRR_{1\ min}$ and $HRR_{5\ min}$, respectively. The complete set of data is also summarised in Table 3 for completeness.

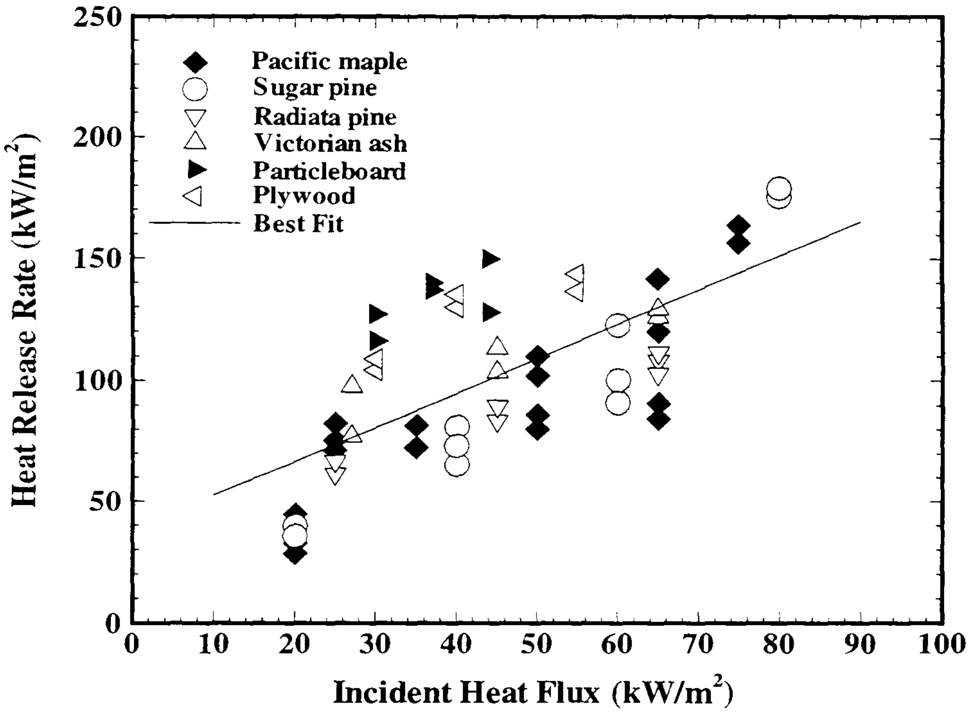

Figure 3: Five-minute average HRR of six wood materials.

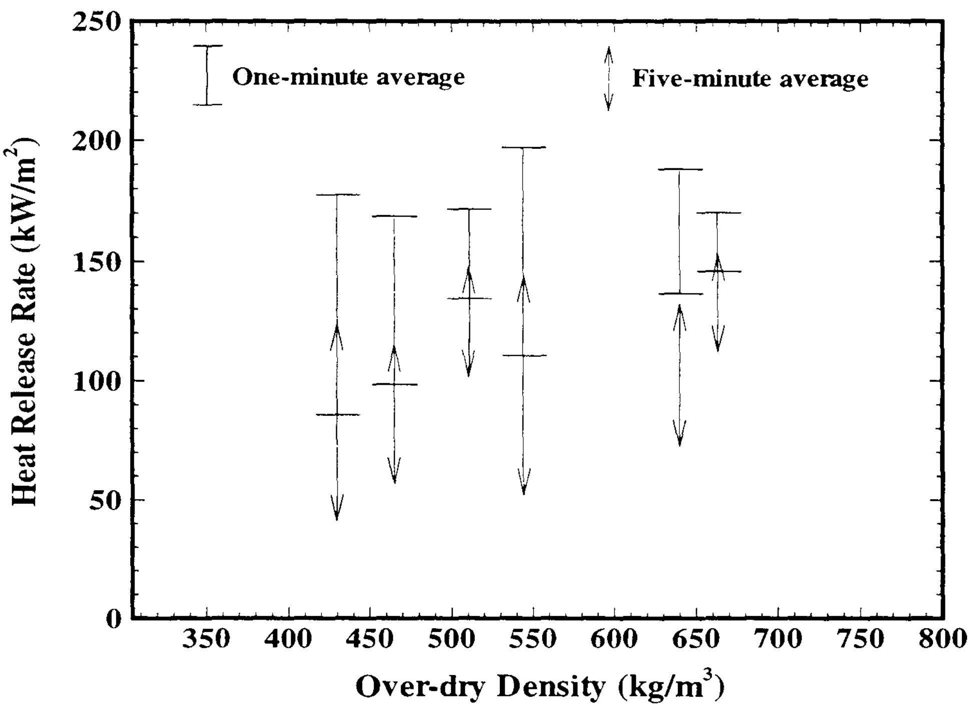

Figure 4: One-minute and five-minute average heat release rates of six wood materials as a functic of oven-dry density.

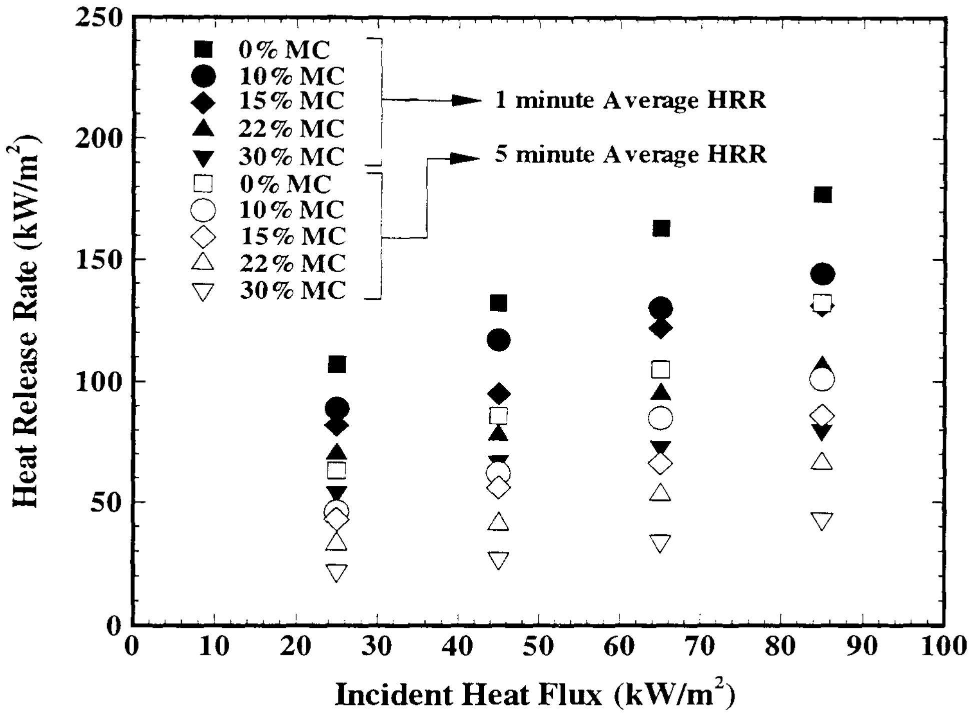

Figure 5: The effect of moisture content on the average heat release rate of Radiata pine.

Heat Flux (kW/m^2)	*1 min HRR* (kW/m^2)					*5 min HRR* (kW/m^2)				
	%MC					*%MC*				
	0	10	15	22	30	0	10	15	22	30
Radiata pine										
25	107	89	82	66	54	61	50	43	33	22
45	132	117	95	82	65	86	62	56	41	27
65	163	130	122	95	73	105	85	72	53	34
85	177	144	131	106	80	132	101	86	66	43
Pacific maple										
25	118	97	86	71	54	71	57	47	35	22
45	147	122	108	89	68	90	65	57	46	31
65	175	141	120	107	83	117	91	78	60	34
85	193	160	141	114	89	131	103	88	62	42
Sugar pine										
25	90	---	66	55	42	55	---	36	27	17
45	120	---	88	73	55	82	---	51	42	27
65	140	---	100	81	66	110	---	74	51	31
85	161	---	120	98	74	127	---	83	63	42
Victorian ash										
25	135	110	---	---	---	86	64	---	---	---
45	162	134	---	---	---	110	86	---	---	---
65	187	151	---	---	---	133	105	---	---	---
85	202	166	---	---	---	141	110	---	---	---

Table 3: Average HRR of conditioned and oven-dry specimens of four wood species

As Figure 5 and Table 3 show, the effect of moisture content is quite significant. Based on the present set of data, for every 1% increase in the moisture content level $HRR_{1\,min}$ and $HRR_{5\,min}$ decrease about 1.8% and 2.3%, respectively. This can be represented by the following expressions

$$HRR_{1\,min} = HRR_{1\,min}^{0}(1 - 0.018 \times \%MC) \quad (3)$$

$$HRR_{5\,min} = HRR_{5\,min}^{0}(1 - 0.023 \times \%MC) \quad (4)$$

where $\%MC$ represents the percent of moisture content and superscript '0' refers to 0% moisture content. These relationships are consistent with those reported by Tran [6]. However, the present results should be more reliable than those of Tran, because he conducted his experiments for only one level of moisture content ($\%MC = 9\%$) at a single irradiance of 50 kW/m^2.

The experimental data of the third set of tests were used to investigate the effect of orientation on HRR. As pointed out in an earlier work [4], the effect of orientation on the piloted ignition characteristics of solid fuels is negligible. However, this is not the case for the flaming combustion characteristics. In particular, the results of the present study reveal that the heat release data for wood materials are quite sensitive to the effect of orientation. Based on the present set of data, the heat release rates obtained in the horizontal orientation for Pacific maple and Radiata pine are about 28% higher than those obtained in the vertical orientation. Certainly, the database in not adequate to characterise the effect of orientation satisfactorily. However, it highlights the role of orientation in bench-scale tests.

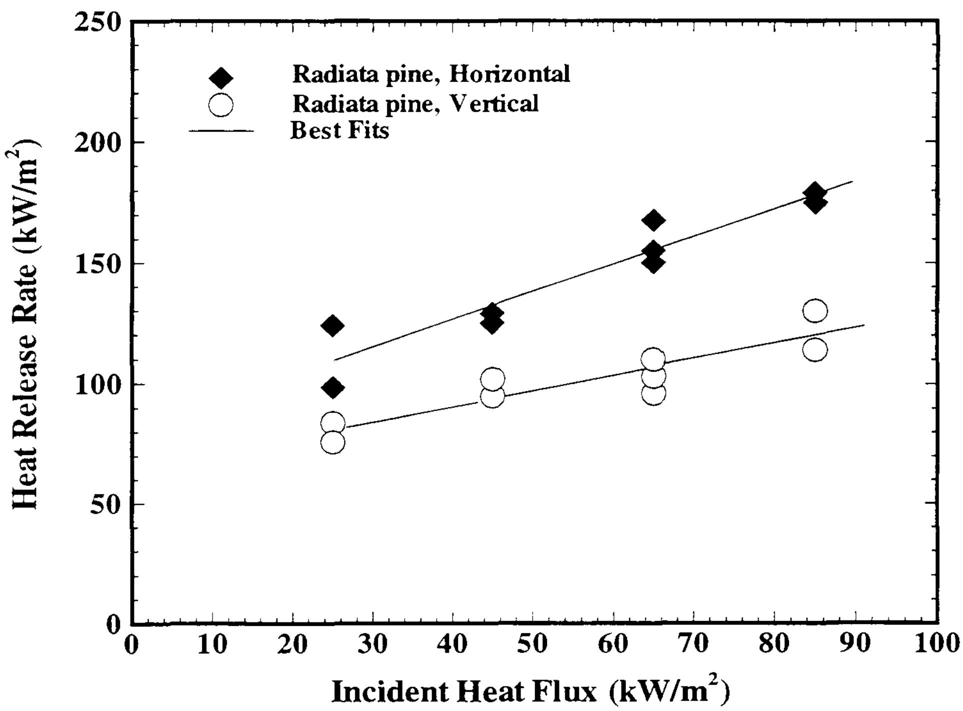

Figure 6: One-minute average heat release rates of Radiata pine specimens tested in the horizontal and vertical orientations.

For Radiata pine, Figure 6 shows a summary of the heat release rate data obtained in both horizontal and vertical orientations. From a physical point of view, the higher HRR in the horizontal orientation can be attributed to the radiation feedback from the flame which is significantly affected by the shape of the flame. In the vertical orientation, the flame forms a thin sheet which covers the exposed surface of the sample. As a result, the gas phase combustion occurs primarily above the upper edge of the sample. However, in the horizontal orientation the flame takes a conical shape that has a much greater volume. This enhances the gas phase combustion which in turn results in a higher level of radiative feedback to the sample.

HEAT OF COMBUSTION

One of the main combustion characteristics of solid fuels is the effective heat of combustion because it can be used to estimate the HRR if the mass loss rate of burning material is known. The main focus here is on the average value of the effective heat of combustion (HOC_{av}) during the flaming period. In bench-scale tests, including the experiments performed in this study, HOC_{av} is obtained from the total heat release during the burning period divided by the total mass loss. Figure 7 shows a typical set of results for oven-dry and conditioned specimens of Pacific maple. As shown in this figure, for Pacific maple, the effective heat of combustion varies with irradiance in a linear fashion. Similar results were obtained for other materials tested in this study.

For wood, the effective heat of combustion is also complicated by a number of other factors including the moisture content (see Figure 7). However, based on the information available, the following simple relationship is proposed for the effective heat of combustion of wood materials over a range of irradiance level between 20 and 85 kW/m^2:

$$HOC_{av} = (0.075 \times \dot{q}_e'') + (10.21 - 0.027 \times \%MC) \quad \textbf{(5)}$$

where HOC_{av} is expressed in MJ/kg. Note that in equation (5) the effects of both incident heat flux and moisture content have been taken into account.

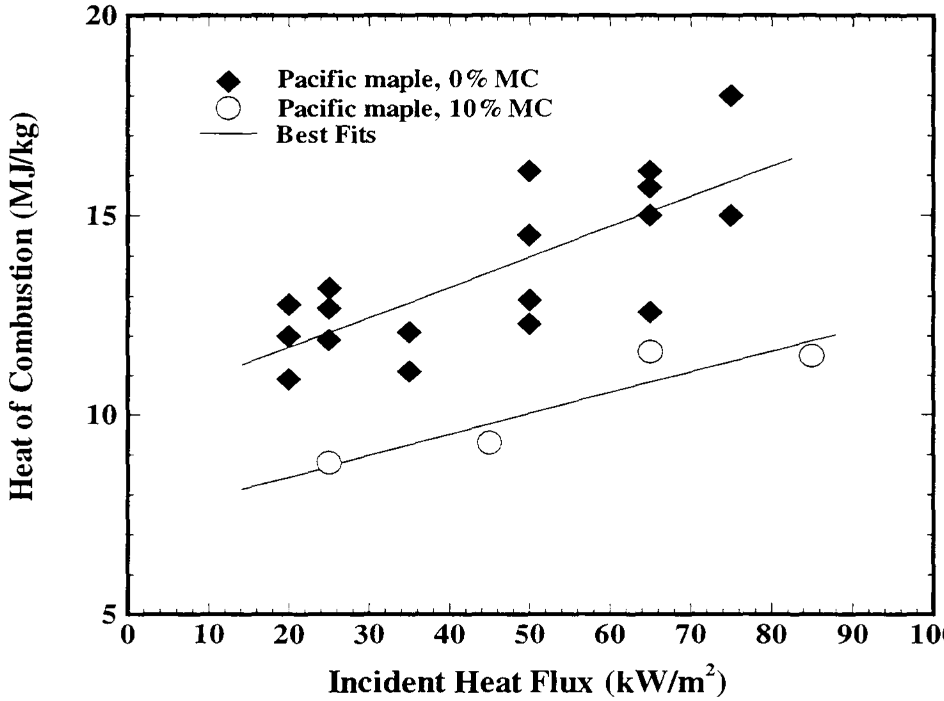

Figure 7: Effective heat of combustion of oven-dried and conditioned specimens of Pacific maple.

CONCLUSIONS

The present work is concerned with the flaming combustion characteristics of wood-based materials. In order to study these characteristics a number of small-scale experiments were performed on different Australian wood species in a cone calorimeter. One of the main objectives was to investigate the effects of the external and internal factors on the flaming combustion characteristics of wood. This study leads to the following conclusions which are quite consistent with those reported by other researchers:

1. both heat release rate and heat of combustion of wood-based materials are significantly affected by the irradiance level, density, moisture content and orientation of the sample;

2. the heat release rate increases with increase in the irradiance level;

3. the higher the moisture content the lower the heat release rate;

4. the heat release rate in the horizontal orientation is much higher than that of the vertical orientation, mainly because the amount of radiative feedback from the flame in much more stronger (for some species the difference was about 28%);

5. the effective heat of combustion of wood-based materials varies with irradiance level in a linear fashion;

6. the effective heat of combustion is also complicated by the moisture content of the material (the higher the moisture content the lower the heat of combustion).

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