J Wood Sci (2009) 55:453–457
DOI 10.1007/s10086-009-1061-1

ORIGINAL ARTICLE

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Evaluation of combustion properties of wood pellets using a cone calorimeter

Received: May 29, 2009/ Accepted: August 24, 2009 / Published online: November 5, 2009

Abstract In this study, the combustion properties of wood pellets were evaluated using a cone calorimeter, which is usually used to verify the fireproof performance of architectural materials. In contrast to the conventional methods including combustion calorimetry and thermogravimetric analysis, a cone calorimeter can estimate various combustion parameters, e.g., changes of heat release rate (HRR), weight decrease during burning process, ignition time, and flame-out and burn-out time as well as combustion heat, in a single experimental run with no pretreatment for sample size reduction. The following results were obtained by the combustion test of Japanese cedar (*Cryptomeria japonica*) and larch (*Larix kaempferi*) wood pellets having various volume densities. Ignition time of wood pellet became slower with increasing volume density of the pellets. However, burn-out time was not clearly correlated to volume density. The heat release values measured by cone calorimeter could be comparable to those from the conventional combustion calorimeters, and flaming heat values of the bark pellets were always lower in comparison with pellets made of xylem, although total heat release was almost the same.

Key words Wood pellet · Cone calorimeter · Combustion property · Volume density

Introduction

For reasons of current environmental concerns, biomass has been receiving much attention as a renewable resource, the utilization of which could mitigate global warming issues caused by carbon dioxide emission. For this reason, various utilization methods have been proposed for forest biomass. Among them, wood pellets would be one of the most promising methods to produce biomass fuel, which could be an alternative to fossil fuels as a heat resource.

Wood pellets can be produced from wood processing residues such as sawdust, planer shavings, and bark by compressing them into cylindrical form through a pelletizing die with relatively low energy consumption. Wood pellets have various advantages as solid biomass fuels in comparison with wood chips and firewood, e.g., higher energy density (per volume), lower moisture content, and better handling properties. Therefore, worldwide production of wood pellets has been substantially increasing in recent years. As the pellet market grew, unexpected troubles have been reported, such as hard ignition, unburnt pellets, and incomplete combustion. Combustion calorimeters have been widely used to evaluate the combustion properties of various fuels including wood pellets.[1] The calorimeters can calculate the heat release value of various shapes of sample when it is completely combusted under aerobic conditions. Unfortunately, the calorimeter cannot trace the entire combustion behavior of the burning process. To trace the combustion behavior of solid fuels, thermogravimetry/differential thermal analysis (TG/DTA) has also been used on a laboratory scale. However, because sample size significantly affects the analytical results, it is generally required to grind the sample into a fine powder before measurement.[2]

To evaluate the fireproof performance of architectural materials such as wood and wood panels, a corn calorimeter is conventionally used.[3,4] By the use of a corn calorimeter, it could also be possible to trace combustion properties and the whole combustion behavior of burning processes of wood pellets with no pretreatment such as pregrinding.

In this study, the combustion behavior of wood pellets was examined using a corn calorimeter to evaluate the effects of physical properties of wood pellets on their combustion properties.

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Part of this report was presented at the 59th Annual Meeting of the Japan Wood Research Society in Matsumoto, March 2009

Table 1. Volume density of wood pellets prepared in this study

Species	Parts	Volume density (g/cm^3)	Sample no.
Larch	Xylem and bark (mixed)	1.19	LM-1[a]
		1.24	LM-2
		1.31	LM-3
	Bark	1.17	LB-1[a]
		1.17	LB-2
		1.22	LB-3
Cedar	Xylem (white)	1.09	CW-1
		1.12	CW-2
		1.15	CW-3
		1.28	CW-4
		1.31	CW-5
		1.32	CW-6
	Bark	1.10	CB-1[a]
		1.19	CB-2
		1.24	CB-3
		1.30	CB-4
		1.32	CB-5

[a] Commercial products

Experimental

Preparation of wood pellets

Japanese cedar (*Cryptomeria japonica*) and larch (*Larix kaempferi*) wood were used as raw materials. As listed in Table 1, wood pellets were made from the mixture of xylem and bark (mixed pellet) or from bark only (bark pellet) for larch, and from xylem only (white pellet) or from bark only for cedar. Before pelletizing, the wood samples were crushed to <4 mm by the hammer mill and dried to a moisture content of ~15% and ~20% for xylem and bark samples, respectively. The flat-die type pelletizer with 6.2 mmϕ of a hole-diameter (type KP280; Kikukawa Iron Works, Japan) was employed in this research. By changing the die thicknesses (28 or 35 mm), feeding rates (5–30 kg/h), and die temperatures (60°–95°C), pellets having various volume densities were prepared. These pellets were stored in a temperature/humidity-controlled room at 20°C and RH of 40% before the combustion tests. Apparent volume densities of the pellets were stereometrically determined; the results are listed in Table 1 as the average of 50 measurements. The moisture content of pellets was ~10% and 10%–19% for white and mixed pellets and bark pellets, respectively.

Combustion test of wood pellets

A model C3-type cone calorimeter (Toyoseiki, Japan) was used in this research. Pellets were horizontally lined up in the stainless steel pan (W × D × H = 100 × 100 × 6.5 mm) designed for cone calorimetric analysis (Fig. 1). The sample pan was set into the sample holder, and placed on the holder pedestal connected to the load cell. The igniter rod was set just above the samples, and 50 kW/m^2 of heat was continuously irradiated to the samples under air atmosphere. After ignition, the rod was immediately removed. During the test, oxygen concentration of the exhaust gas and the sample weight were recorded every 2 s on a PC. The heat release rate (HRR) was calculated by the oxygen consumption on a lower heat value (LHV) basis.[5] The HRR is generally described as the heat generated rate per heated area (kW/m^2) for the fireproof experiment. However, in this experiment, HRR was converted to weight base values so as to compare them with reported values in the literature. Ignition time was determined by visual observation, and flame-out and burn-out times were defined as the points taking HRR values of 50 and 10 kW/m^2, respectively. Residual weight percentage to initial weight was determined from the weight at 2700 s.

Fig. 1. Picture of the sample pan of the cone calorimeter

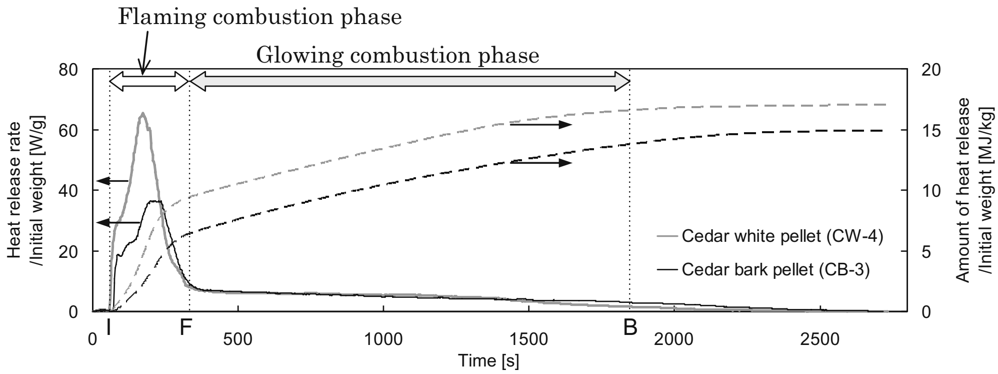

Fig. 2. Profiles for the heat release rate and amount of heat release value per initial weight for wood pellets. *I*, ignition; *F*, flame-out; *B*, burn-out times for CW-4 (cedar white pellet)

Table 2. Results of combustion test by cone calorimetry

Sample no.	Initial weight (g)	Ignition time (s)	Flame-out time (s)	Burn-out time (s)	Total amount of heat release (MJ/kg)[a]	Residual percentage (%)
LM-1	51.69	47.3	314	1642	16.78	0.41
LM-2	56.99	68.4	372	1830	16.49	0.40
LM-3	52.74	74.0	326	1604	15.47	0.36
LB-1	52.17	59.4	328	2158	16.08	1.19
LB-2	52.44	61.2	338	2148	16.06	1.35
LB-3	54.16	68.4	320	2170	15.96	1.11
CW-1	52.52	35.6	300	1672	16.78	0.76
CW-2	51.21	47.5	288	1620	17.53	0.57
CW-3	48.84	43.1	272	1536	17.14	0.59
CW-4	57.41	53.6	344	1798	17.12	0.70
CW-5	58.41	67.4	312	1822	15.98	0.70
CW-6	59.38	60.1	344	1898	16.48	0.64
CB-1	50.04	42.2	306	2184	17.29	3.14
CB-2	48.82	63.2	352	1920	15.64	2.60
CB-3	55.97	68.8	352	2168	15.54	3.95
CB-4	59.91	59.7	380	2220	14.78	3.51
CB-5	61.13	64.4	372	2384	15.77	2.44

[a]The values were obtained by total amount of heat release per total amount of weight loss

Results and discussion

To evaluate the combustion properties of wood pellets, combustion experiments of Japanese cedar and larch wood pellets were conducted by means of a cone calorimeter. The typical HRR profiles and their integration curves (amount of heat release) for cedar samples (CW-4 and CB-3) are shown as a function of time in Fig. 2. The total amounts of heat release for all samples are summarized in Table 2 together with ignition, flame-out, and burn-out times and residual weight percentage. The combustion process can be separated into two different phases: flaming and glowing. During the flaming combustion phase, HRR drastically increased soon after the ignition point (point I in Fig. 2) and decreased after the maximum point to the flame-out point (point F in Fig. 2). By contrast, HRR moderately decreased until the burn-out point (point B in Fig. 2) during the glowing combustion phase. During the course of the burning process of wood pellets, the glowing combustion phase took more time than the flaming combustion phase in this test condition. In comparison with the white pellets, the bark pellets showed slower combustion. For instance, the profiles of CB-3 gave longer ignition times (68.8 s), flame-out times (352 s), and burn-out times (2168 s) compared with those of CW-4. The total amounts of heat release for the samples were evaluated to be 14.8–17.5 MJ/kg by a cone calorimeter. The LHV calculated from higher caloric values from the literature,[6–8] which was measured by combustion calorimetry, were in the range of 14.6–16.3 MJ/kg for the white, bark, and mixed pellets. These results indicate that the total amount of heat release might correspond to the LHV calculated by the conventional calorimetry method. The total amount of heat release for bark pellets (15.8 and 15.3 MJ/kg in averages for LB and CB, respectively) was somewhat lower than for white pellets (16.7 MJ/kg for CW). The residual weight percentages of white pellets were 0.57%–0.76%, which were lower than the bark pellets (1.11%–3.95%). It was reported that the average ash contents of bark pellets and white pellets were 4.6% and 0.42%, respectively.[6] Although the results of the combustion residues varied among the samples, the higher ash content would be one of the reasons for the higher combustion residues of the bark pellets in comparison with the white pellets.

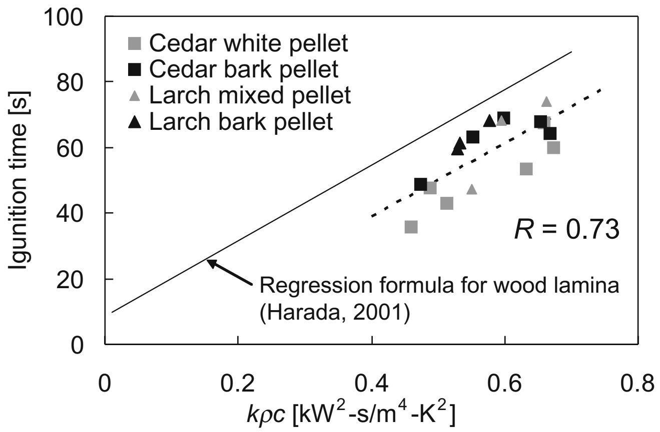

Fig. 3. Relationship between ignition time and heat inertia for four types of pellets

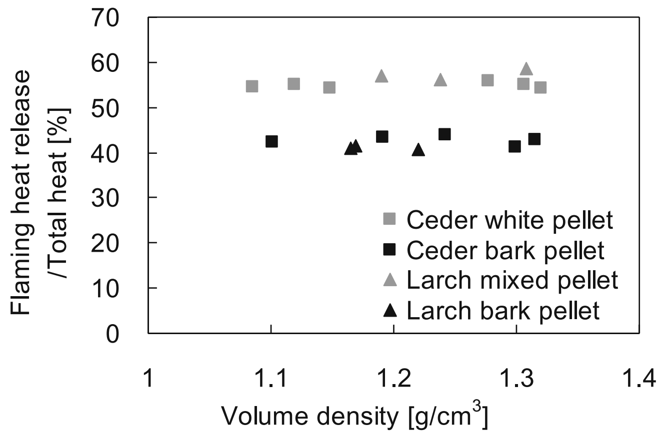

Fig. 4. Ratio of amount of heat release during flaming combustion to total heat release

Ignition time

Assuming that the thickness of the materials is infinite, ignition time (t_{ig}) under constant heating can be described by Eq. 1:[9]

$$t_{ig} = \pi k \rho c \left(\frac{T_{ig} - T_0}{2\delta I} \right)^2 \tag{1}$$

where k is thermal conductivity, ρ is volume density, c is specific heat, T_{ig} is ignition temperature, δ is absorptance, and I is heating intensity. According to Harada,[10] t_{ig} was also determined by the following empirical formula (Eq. 2):

$$t_{ig} = 14.4 \times 10^6 \times \frac{\pi k \rho c}{I^3} + 8.64 \tag{2}$$

These formulations explain that the ignition time is proportionally related to heat inertia, $k\rho c$. To verify the applicability of these equations to wood pellets, t_{ig} of each sample was plotted against $k\rho c$. Specific heat "c" was considered to be 1.25 kJ/kgK.[11] There are no data for k value for wood pellets. In this study, the average k value of wood of radial and fiber directions was employed. The k value of wood for each direction was calculated from ρ values individually using formulae suggested by Urakami and Fukuyama,[12] and Maku.[13] Figure 3 shows the relationship between $k\rho c$ and t_{ig} for wood pellets. The $k\rho c$ was proportionally related to the longer t_{ig} (dotted line in Fig. 3; $R = 0.73$). The slope of this line was roughly the same as the regression line drawn for the wood samples calculated from Eq. 2, which means that t_{ig} of wood pellets could be assumable from their volume density values, i.e., pellets with higher volume density require longer ignition time. However, the t_{ig} for the wood pellets was always shorter than that for wood laminates. Ignition occurs when the concentration of combustible gases reaches the flammable concentration limit. Combustible gases are generated by thermal decomposition of the samples. Larger amounts of decomposition gases could be generated from samples having a larger surface area in comparison with samples having lesser surface area, when sufficient amounts of heat were irradiated during the combustion test. Therefore, shorter t_{ig} values for pellet samples would be caused by large apparent surface area consequent to their cylindrical form.

Heat release ratio of wood pellets during flaming and glowing combustion phases

Figure 4 shows the ratio of heat release amount during flaming combustion to the total heat release. There is an obvious difference between the parts of the wood. The ratio was higher for the white and mixed pellets (54%–58%) than the bark pellets. In other words, heat was mainly released during the glowing combustion phase for the bark pellets. However, there were no clear correlations between the heat release ratio and the volume density of wood pellets.

Burn-out time

Rhén et al.[14] reported that the char combustion time (equal to the period of glowing combustion) was positively correlated to the volume density of the samples. In our experiment, it was also found that burn-out time was correlated with the volume density of Japanese cedar and larch wood pellets (refer to Table 2). Moreover, burn-out time was highly correlated with the weight at the flame-out point (Fig. 5). These observations indicate that burn-out time of wood pellets could be predictable from volume densities and the weight at flame-out point.

Conclusions

The cone calorimeter was applied to evaluate the combustion properties of Japanese cedar and larch pellets, and it was demonstrated that multiple characteristics can be obtained with this test method in comparison with conventional calorimetry. From the results, the following points were concluded:

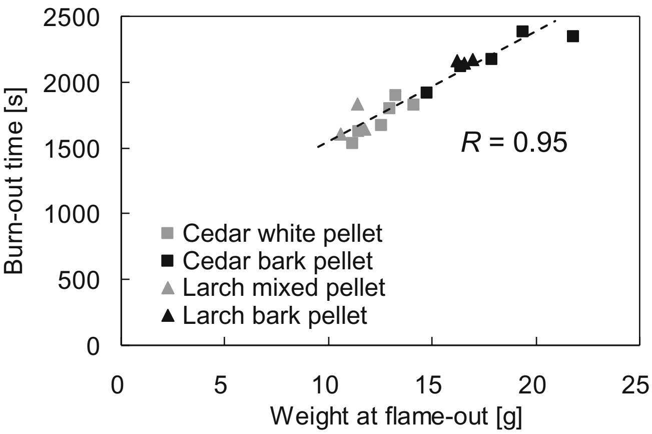

Fig. 5. Relationship between burn-out time and weight at flame-out point

1. Ignition time is closely related to the densities of pellets. Ignition time of a wood pellet with higher volume density is longer than that of a pellet with lower volume density.
2. Relative combustion heat during flaming to total heat release depends on the part of wood. For example, flaming heat value of the bark pellets is always lower in comparison with pellets made of xylem, although total heat release is almost the same.
3. Burn-out time is closely related to the residual weight at the flame-out time.

The results indicate that the cone calorimeter can evaluate the combustion properties of wood pellets, and some relationships were demonstrated between physical properties of wood pellets and combustion behavior. The results indicate that the cone calorimeter can evaluate the combustion properties of wood pellets and could be of great use to improve the quality of wood pellets.

Acknowledgments This research was supported by research grant #30153 from the Forestry and Forest Products Research Institute, Tsukuba, Japan.

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