COMBUSTION PROPERTIES OF NATIVE KOREAN WOOD SPECIES

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(Received 10 November 2008; Accepted 18 December 2008)

ABSTRACT

This paper investigates the combustion characteristics of four wood species native to Korea. The species examined were Oak, Pitch Pine, Chestnut Tree, and Zelkova. The cone calorimeter was used to measure the heat release rate, smoke production and toxic gas yields.

1. INTRODUCTION

Combustion is associated with a variety of material properties. These properties determine the rate at which heat is released from the material when it burns, the smoke production and the toxicity of the gases. Wood is composed of three basic polymers: lignin, cellulose and hemicellulose and contains about 43% cellulose, 22-29% lignin, and 28-35% hemicellulose (on an extractive free basis) [1]. Lignin in wood is an amorphous polyphenolic plant constituent. Its aromatic chemical structure is able to give a very high char yield which can still reach 35-38% at 900°C [2]. The char reduces the combustion rate of polymer materials because it does not allow the oxygen to reach the combustion zone easily [3]. Species of wood have different polymer compositions and are broadly categorized as hardwoods or softwoods where softwoods have a higher lignin content and lower hemicellulose than hardwoods [4]. These differences in composition cause varying calorific values among wood species; however, wood with a high extractive content would have a high calorific value [5]. A maximum calorific value of wood is considered to be about 17 $MJkg^{-1}$ [6] although actual measured values may be somewhat lower due to variations in the char yield and moisture content [7-9]. Moisture in wood is an important factor in its energy generation and wood with high moisture content will not burn easily [10]. The density of wood also varies between species and with the moisture content so that it is necessary to refer to moisture condition when noting the density of wood [11]. When wood is burned it produces a smoky emission accompanied by the deposition of tar and soot [10,12]. If incomplete combustion of wood occurs, which is mostly the case, products such as carbon monoxide, nitrous oxides, sulphur oxides, polycyclic aromatic hydrocarbons and particles will be emitted [13].

2. EXPERIMENTAL

The samples used in this work were wood species native to Korea and were obtained directly from a local farmer. The four species of wood used in the tests, including scientific names and the water content measured by following ISO 3130 [14], are listed in Table 1. The duration between cutting-down trees to burning each wood species was about two years except for the Oak which had been stored for about one year. The average bulk density of samples was calculated from its weight and volume recorded prior to testing.

Table 1: Properties of wood species used in tests

Samples	Scientific name	Class	Density (kgm^{-3})	Moisture content (%)
Pitch Pine	*Pinus rigida*	Softwood	419	10
Chestnut Tree	*Castanea sativa*	Hardwood	654	11
Oak	*Quercus acutissima*	Hardwood	928	14
Zelkova	*Zelkova serrata*	Hardwood	619	10

The cone calorimeter [15] was used to determine the following principal properties: heat release rate (HRR), and fire smoke index [16,17], as well as CO and CO_2 production and smoke obscuration [18]. Wood specimens with dimensions 100 mm by 100 mm by 10 mm thick were conditioned at 50% R.H. and 23°C prior to the cone calorimeter tests. The specimen was placed on a low density ceramic fiber blanket, backed by a high density ceramic fiber board. An edge frame was used to minimise edge effects. The materials were tested in the horizontal orientation at an external irradiance 50 kWm^{-2} to represent fully developed compartment fire conditions. Tests were terminated when the average value of mass loss rate over a period of one minute dropped below 150 gm^{-2}, as specified in the ISO 5660 standard. All the tests were carried out three times to ensure their reproducibility.

3. RESULTS

3.1 Heat Release Rate

HRR curves of native wood species exposed to the external heat flux are shown in Fig. 1 and exhibit the characteristic profile expected for wood samples tested in the cone calorimeter. The curves have an initial peak as the surface of the sample ignites followed by a reduction in HRR as a result of the insulation effect of the char layer that slows down the pyrolysis of virgin wood and thus the amount of fuel that is available. The subsequent increase in HRR close to the end of a test is due to the back effect where the burning rate of the sample increases as the thermal wave is reflected at the rear of the sample. The average HRR of the Oak at 50 kWm^{-2} was 183.1 kWm^{-2} in comparison with 150.7, 160.7 and 94.0 kWm^{-2} for the Pitch Pine, Chestnut Tree, and Zelkova respectively (Table 2). Chestnut Tree reached a peak HRR at 290 s whereas the Oak reached a peak HRR at 415 s and only the Zelkova burned for a longer time than the Oak. Since wood that has high carbon content will generate more heat than others [12] these results suggest that the Oak has a high carbon content compared to the other species tested.

Fig. 2 shows total heat release (THR) curves of native species wood at 50 kWm^{-2}. As would be expected, the THR curves mirror the HRR curves and they show the higher heat content of the Oak compared to the Pitch Pine, Chestnut Tree and Zelkova. The THR curves show that the combustion of Oak is delayed in comparison with Pitch Pine and Chestnut Tree. At the end of combustion, THR values given in Table 2 for the Pitch Pine, Chestnut Tree, Oak, and the Zelkova measured at 50 kWm^{-2} are different. These differences can be attributed to the post-glowing phenomenon which occurs at long times in the combustion of the Oak and slightly longer times for the Zelkova.

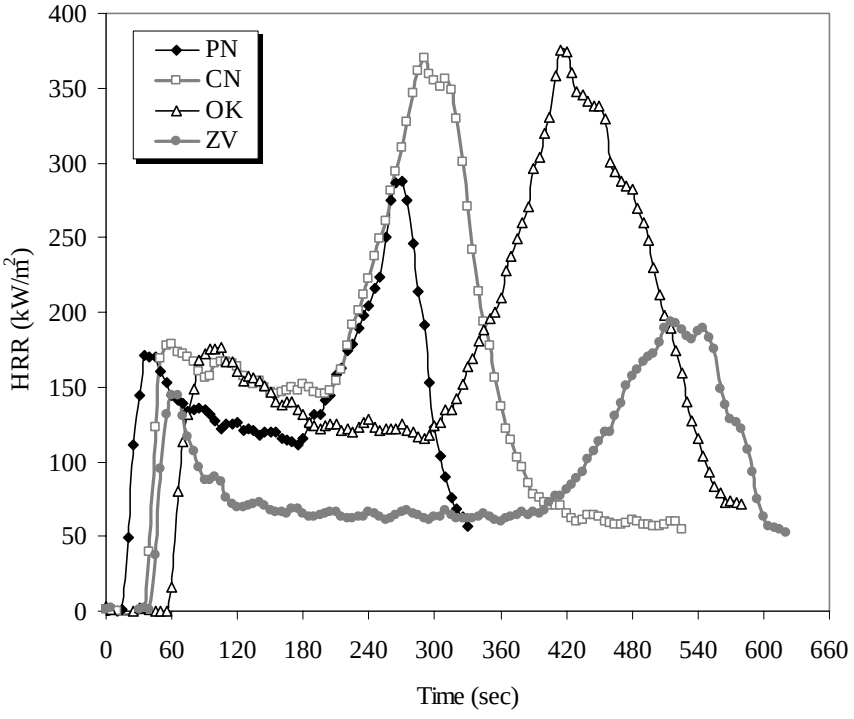

Fig. 1: HRR curves of native Korean wood species at 50 kWm^{-2} external heat flux (PN: Pitch Pine, CN: Chestnut Tree, OK: Oak, ZV: Zelkova)

Table 2: Combustion properties of native wood species grown in Korea

Samples	[a] HRR_{mean} (kWm^{-2})	[b] THR (MJm^{-2})	[c] SEA (m^2kg^{-1})	[d] FT (s)	CO_{mean} ($kgkg^{-1}$)	$CO_{2,\ mean}$ ($kgkg^{-1}$)	CO/CO_2
Pitch Pine	150.7	46.8	51.55	313	0.0083	1.14	0.0072
Chestnut Tree	160.7	78.0	31.67	488	0.0148	1.21	0.0122
Oak	183.1	94.6	24.47	518	0.0079	1.14	0.0069
Zelkova	94.0	54.1	13.22	579	0.0127	1.04	0.0817

[a] Heat release rate; [b] Total heat release; [c] Specific extinction area; [d] Flaming time

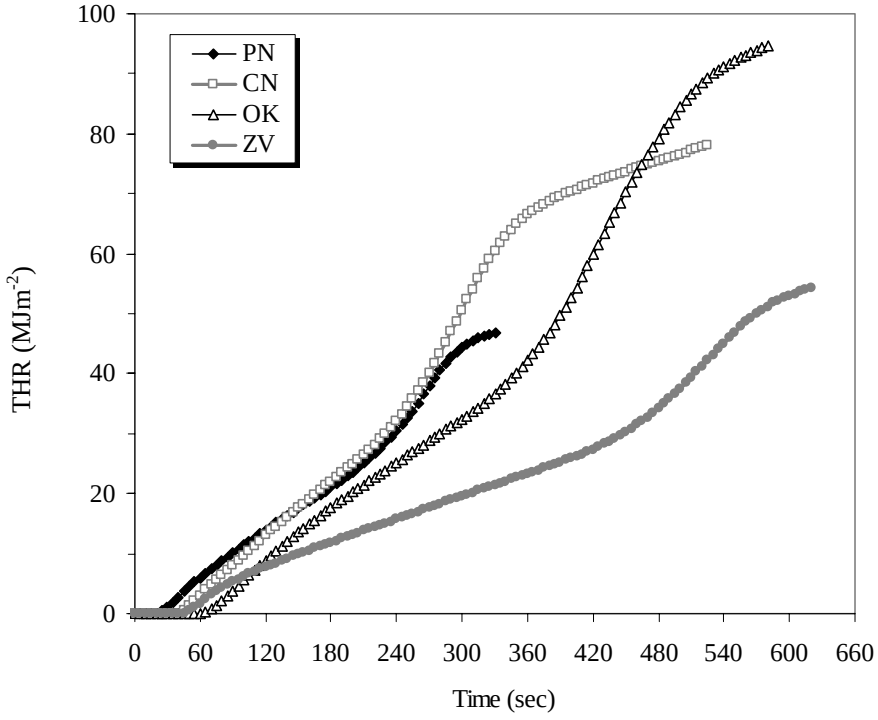

Fig. 2: THR curves of native wood species at 50 kWm^{-2} external heat flux (PN: Pitch Pine, CN: Chestnut Tree, OK: Oak, ZV: Zelkova)

Char formation was observed by the naked eye so the thickness was not measured nevertheless it is important to notice that the residues of the four materials at end of the combustion were completely different (Fig. 3). Although the samples in each case had completely charred through, the residues of the Oak and the Pitch Pine consisted of only white colour ashes as compared to the residues of the Chestnut Tree and the Zelkova which presented aspects similar to those observed at the early stages of the experiments. The residues from these two species were small black colour pieces of hard material although they had very weak mechanical properties.

3.2 Effective Heat of Combustion

The average effective heat (EHC) of combustion was found for each species (Table 3) by dividing the total heat released by the total mass loss over the duration of the test. Table 3 illustrates the effect of moisture content on the calorific value of wood. The Pitch Pine and the Chestnut Tree gave calorific values of 12.26 $MJkg^{-1}$ and 12.67 $MJkg^{-1}$, respectively. Oak has a smaller calorific value (11.42 $MJkg^{-1}$) because of its high moisture content in comparison with the other species tested. As already noted, Chestnut Tree and Zelkova exhibited similar char formation and Zelkova in particular has a strong retardant property as shown in Fig. 3.

(a) Pitch Pine (b) Chestnut Tree

(c) Oak (d) Zelkova

Fig. 3: Native wood before burning and the residues of native wood after combustion

Table 3: Average effective heat of combustion for each species

Species	Effective heat of combustion ($MJkg^{-1}$)
Pitch Pine	12.26
Chestnut Tree	12.67
Oak	11.42
Zelkova	9.74

3.3 Smoke and Carbon Oxides

The smoke production rate (SPR) of the Oak and the Zelkova samples was lower than that of the Pitch Pine and Chestnut Tree (Fig. 4). The Pitch Pine and Chestnut Tree evolved smoke with a peak of 0.023 m^2kg^{-1} at 280 s and 0.0125 m^2kg^{-1} at 45 s, respectively. The Oak and the Zelkova mildly contributed to smoke obscuration during combustion whereas the smoke production of burning in the Pitch Pine and the Chestnut Tree was comparatively high. Smoke opacity is given as average specific extinction area (SEA). The specific extinction area of the Oak and the Zelkova is lower than that of the Pitch Pine and the Chestnut Tree (Fig. 5). The Pitch Pine and the Chestnut Tree evolved smoke with a peak at 51.55 m^2kg^{-1} and 31.67 m^2kg^{-1} respectively.

Yields of CO and CO_2 depend on the material burning and the ventilation conditions [19]. Fig. 6 presents the CO production versus time evolved in the cone calorimeter. The amount of CO evolved by the Oak is generally lower than that of the Pitch Pine, Chestnut Tree and the Zelkova. It is also interesting to note that the production of CO from the Oak and the Pitch Pine generally decreased with time such that incomplete combustion reactions of the Pitch Pine and the Oak depend on time. This phenomenon is not observed in the case of the Chestnut Tree and the Zelkova. It should also be noted that peak CO production from the Chestnut Tree and Zelkova is relatively high (44 ppm at 526 s for Chestnut Tree and 25 ppm at 623 s for Zelkova) in comparison with that of the Oak and the Pitch Pine, which was evolved at 17 ppm at 440 s and 20 ppm at 277 s, respectively.

The Oak and the Chestnut Tree evolved comparatively high CO_2 yields with a peak of 3235 ppm at 434 s and 3058 ppm at 294 s respectively in comparison with that of the Pitch Pine and Zelkova, which were evolved at 2161 ppm at 273 s and 1647 ppm at 511 s, respectively (Fig. 7). Higher yields of CO_2 generally indicate that a more complete combustion is occurring and exposure toxicity is lower than where the CO/CO_2 ratio is greater.

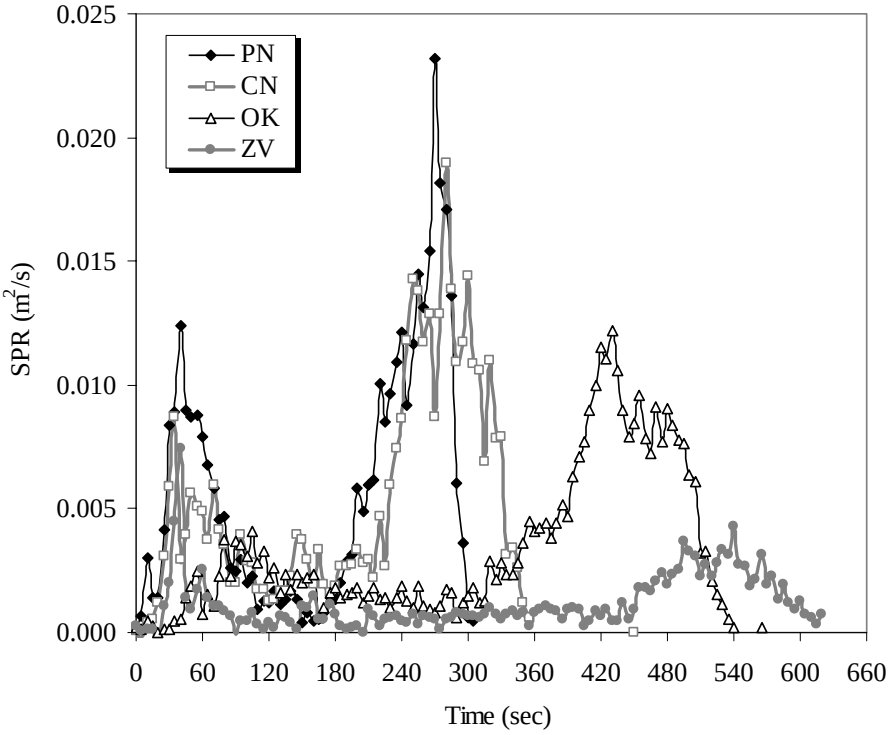

Fig. 4: SPR curves of native wood species at 50 kWm^{-2} external heat flux (PN: Pitch Pine, CN: Chestnut Tree, OK: Oak, ZV: Zelkova)

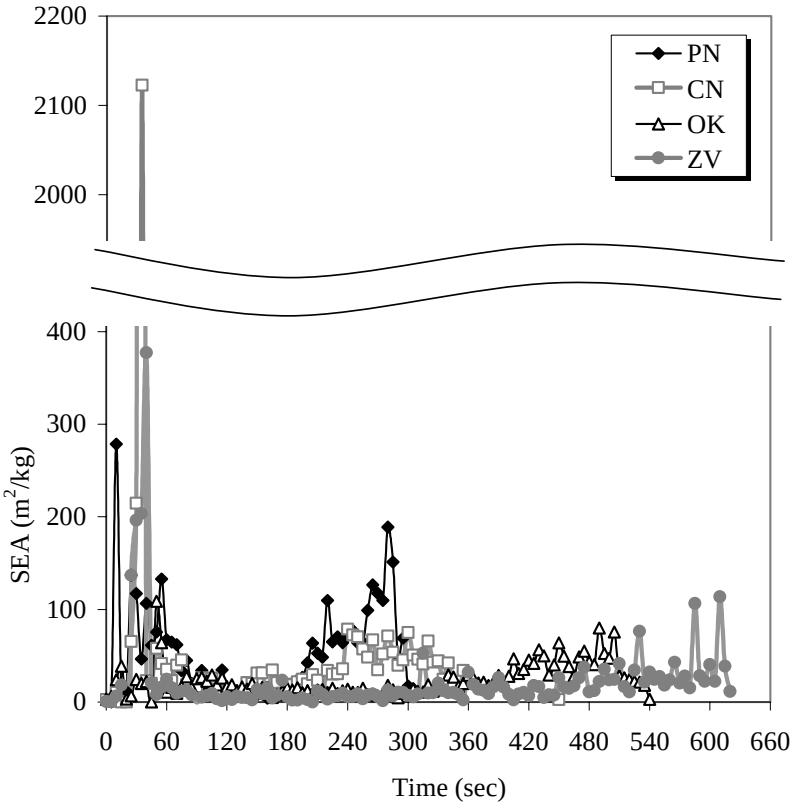

Fig. 5: SEA curves of native wood species at 50 kWm^{-2} external heat flux (PN: Pitch Pine, CN: Chestnut Tree, OK: Oak, ZV: Zelkova)

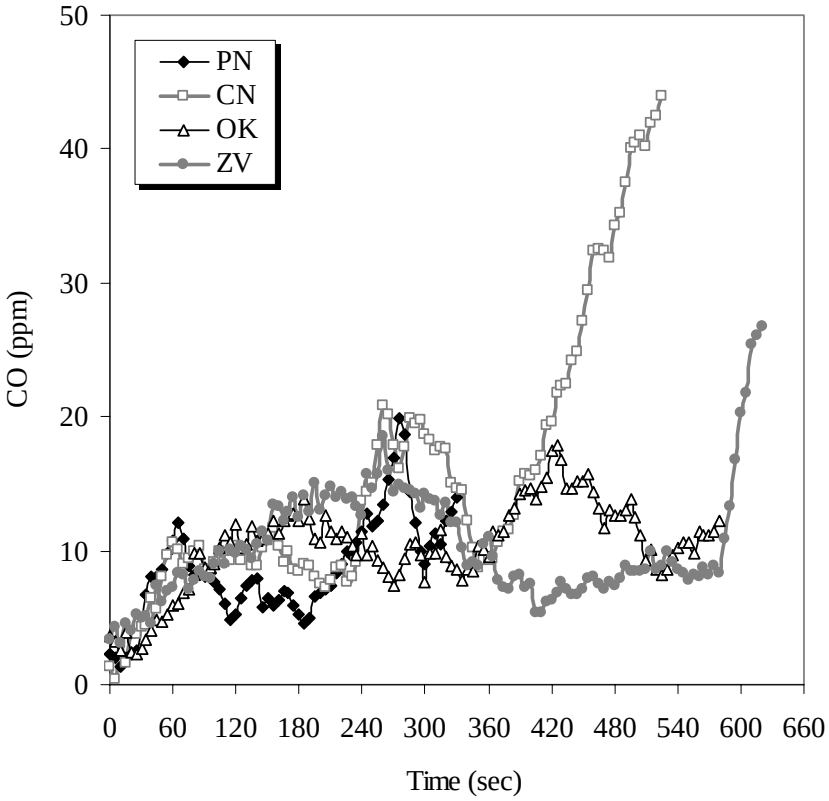

Fig. 6: CO production curves of native wood species at 50 kWm^{-2} external heat flux (PN: Pitch Pine, CN: Chestnut Tree, OK: Oak, ZV: Zelkova)

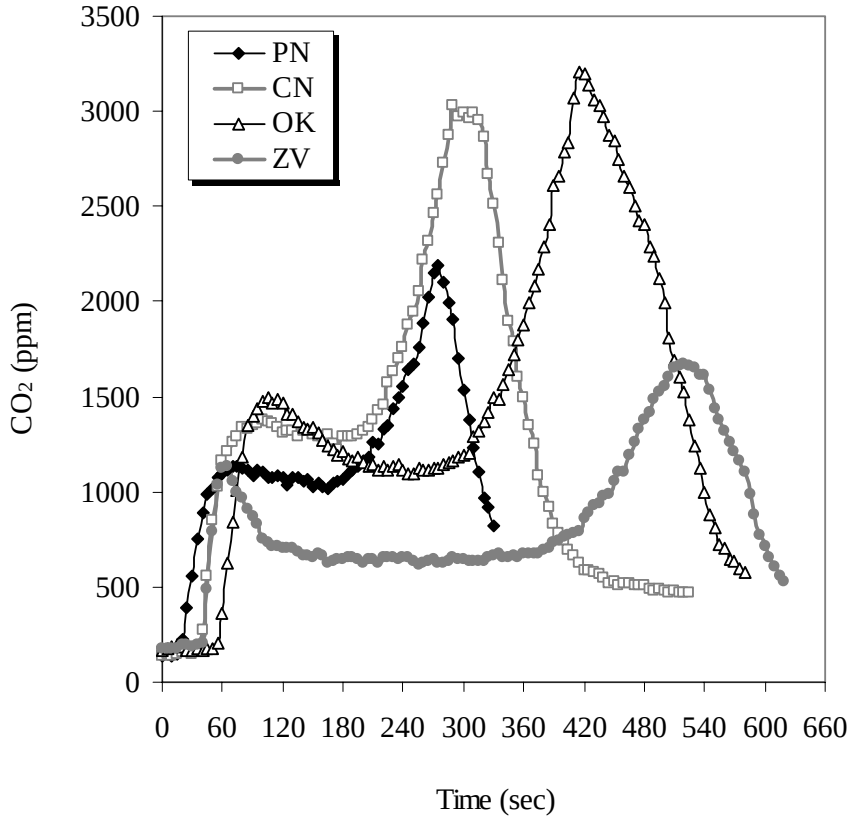

Fig. 7: CO_2 production curves of native wood species at 50 kWm^{-2} external heat flux (PN: Pitch Pine, CN: Chestnut Tree, OK: Oak, ZV: Zelkova)

4. CONCLUSIONS

The heat release rate and smoke production of four species of Korean native wood were measured. Oak gave a calorific value (11.42 $MJkg^{-1}$) because the average heat of combustion was affected by the amount of moisture. However Oak had a high heat release rate (183.1 kWm^{-2}) and high total heat release (94.6 MJm^{-2}) compared with that of Pitch Pine, Chestnut Tree, and Zelkova. Oak burned for a long time (518 s) compared to the other species examined with the exception of Zelkova. The results suggest that Oak has a higher carbon content than the other species. The Oak had a low CO yield (0.0079 $kgkg^{-1}$) and low CO/CO_2 yield (0.0069) compared with that of Pitch Pine, Chestnut Tree and Zelkova. Oak also had a relatively low specific extinction area (24.47 m^2kg^{-1}), because it was almost completely burned during the combustion process.

Data for wood species that are somewhat similar to those tested in this work are available in the literature but any detailed comparisons should be treated with care as individual nominally similar species might differ in properties, samples will vary naturally, moisture contents may not be the same and different test methods may affect results. For example Tran and White [9] used Southern Pine and Red Oak in their modified OSU apparatus and these species might be considered to be similar to Pitch Pine and Oak used in here. However a comparison of densities and moisture contents show that the Southern Pine was 508 kgm^{-3} and 9.71% compared to 419 kgm^{-3} and 10% for the Pitch Pine used here and for Red Oak was 660 kgm^{-3} and 8.53% compared to 928 kgm^{-3} and 14% for the Oak used here. The average HRR obtained by Tran and White at incident heat fluxes close to 50 kWm^{-2} for Southern Pine and Red Oak were 114.7 kWm^{-2} and 112.9 kWm^{-2} respectively compared with 150.7 kWm^{-2} and 183.1 kWm^{-2} for Pitch Pine and Oak respectively. The effective heat of combustion given by Tran and White at incident heat fluxes close to 50 kWm^{-2} for Southern Pine and Red Oak were 13.95 $MJkg^{-1}$ and 11.44 $MJkg^{-1}$ respectively compared with 12.26 $MJkg^{-1}$ and 11.42 $MJkg^{-1}$ for Pitch Pine and Oak respectively. So examining the results for Oak species show a considerable variation in density, moisture and average HRR yet effective heat of combustion values are almost identical. The densities and moisture contents of the Pine species were closer but average HRR and effective heat of combustion values were not correspondingly similar.

ACKNOWLEDGEMENT

The financial support from the Kangwon National University of Korea (Department of Planning & Public Relation, 2007-694) is acknowledged.

REFERENCES

1. F. Shafizadeh and W.F. DeGroot, “Combustion characteristics of cellulosic fuels”, In: F. Shafizadeh, K.V. Sarkenen and D.A. Tillman (editor), Thermal uses and properties of carbohydrates and lignins, Academic Press, New York, USA (1976).
2. A.D. Chirico, M. Armanini, P. Chini, P. Cioccolo, F. Provasoli and G. Audisio, “Flame retardants for polypropylene based on lignin”, Polymer Degradation Stability, Vol. 79, pp. 139-145 (2002).
3. F.M. Pearce, Y.P. Khanna and D. Raucher, “Thermal analysis in polymer flammability”, In: Thermal characterization of polymeric materials, Chapter 8, Academic Press, New York, USA (1981).
4. V. Babrauskas, “Ignition of wood: A review of the state of the art”, Interflam 2001, Interscience Communications Ltd., London, UK, pp. 71-88 (2001).
5. D.A. Tillman, Wood as an energy resource, Academic Press, New York, USA (1978).
6. A.H. Buchanan, Structural design for fire safety, John Wiley & Sons Ltd. (2001).
7. M.J. Spearpoint, Predicting in ignition and burning rate of wood in the cone calorimeter using an integral model, NIST GCR 99-775, National Institute of Standards and Technology, Gaithersburg, USA (1999).
8. V. Babrauskas, “Burning rate”, Chapter 3-1, The SFPE Handbook of Fire Protection Engineering, 3rd edition, National Fire Protection Association, Quincy, MA, USA (2002).
9. H.C. Tran and R.H. White, “Burning rate of solid wood measured in a heat release calorimeter”, Fire and Materials, Vol. 16, No. 4, pp. 197-206 (1992).
10. J.B. Carle and J.L. Brown, “Wood as a source of solid fuel: a review”, G.S. Watt (editor), New Zealand Forest Service, Auckland (1976).
11. N.P. Cheremisinoff, Wood for energy production, Ann Arbor Science Publishers, Ann Arbor, Mich., USA (1980).
12. H. Kubler, Wood as building and hobby material, John Wiley & Sons, Inc., USA (1980).
13. M. Glasius, M. Ketzel, P. Wahlin, B. Jensen, J. Monster, R. Berkowicz and F. Palmgren, “Impact of wood combustion on particle levels in a residential area in Denmark”, Atmospheric Environment, Vol. 40, No. 37, pp. 7115-7124 (2006).

14. ISO 3130, Wood – Determination of moisture content for physical and mechanical tests, International Standards Organization (1975).

15. ISO 5660, Reaction-to-fire tests – Heat release, smoke production and mass loss rate – Part 1: Heat release rate (Cone calorimeter method), International Standards Organization (2002).

16. EN 13823, Reaction to fire tests for building products. Building products excluding floorings exposed to the thermal attack by a single burning item (2002).

17. Y.J. Chung, "Flame retardancy of veneers treated by ammonium salts", Journal of the Korean Industrial & Engineering Chemistry, Vol. 18, pp. 251-254 (2007).

18. V. Babrauskas and S.J. Grayson, Heat release in fires, E & FN Spon (Chapman and Hall), London, UK, 644 pages (1992).

19. R.T. Hull and K.T. Paul, "Bench-scale assessment of combustion toxicity – a critical analysis of current protocols", Fire Safety Journal, Vol. 42, No. 5, pp. 340-365 (2007).