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https://doi.org/10.5109/1526305

出版情報：九州大学大学院農学研究院紀要. 60 (1), pp.197-201, 2015-02-27. Faculty of Agriculture, Kyushu University
バージョン：
権利関係：

KYUSHU UNIVERSITY

J. Fac. Agr., Kyushu Univ., **60** (1), 197–201 (2015)

A Study of The Heating and Energy Efficiency of Thermally–Modified Firewood

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(*Received October 29, 2014 and accepted November 14, 2014*)

This study was performed to evaluate the suitability and burning characteristics of thermally–modified wood for use as auto camping charcoal. Four aspects of the burning were measured using a cone calorimeter: ignition time, total heat released, heat release rate, and flame–out time. In addition, elemental analysis was carried out using an elemental analyzer.

Thermally–modified wood has short ignition and flame–out times because of its low Oxygen/Carbon rate. The total heat released and the heat release rate of thermally–modified wood is higher than that of other wood due to its low oxygen and nitrogen rate and high HHV (Higher Heating Values). With a shorter flame–out time, carbonization takes less time, and the maintenance time is longer. These characteristics of thermally–modified wood make it favorable for use as auto camping charcoal.

Key words: energy efficiency, thermal modification, firewood, ignition time

INTRODUCTION

Wood is a combustible as a result of its primary constituents, cellulose, hemicellulose, and lignin, which are decomposed by heat and consumed to produce heat energy. Charcoal is made by burning pieces of wood to remove impurities, leaving only the coal. Charcoal is generally defined as the carbonized solid product formed from heating timber in the absence of air. The combustion characteristics of charcoal describe how well it ignites and how long it burns. These are important properties to consider when charcoal is used for camping, in addition to the heat produced as a result of combustion.

Quercus variabilis is typically used as the raw material for charcoal. There are 3 types of charcoal. Black coal is cooled slowly in the kiln to a low temperature of approximately 400°C in the absence of air. White charcoal is carbonized at temperatures higher than 800°C in a kiln and then cooled rapidly using wet ashes. Activated charcoal has a greater surface area and higher number of pores than white charcoal.

On the other hand, thermal treatment is one physical modification that can be performed without the addition of chemicals to cause the components of wood to degrade and reform. With thermal treatment at temperatures of 200 to 320°C under atmospheric conditions, parts of the wood such as cellulose, hemicellulose, and lignin decompose and the water and some volatiles are removed (Bergman, 2005). These changes result in the wood more closely resembling charcoal with increasing temperature and treatment time; the color of the wood darkens, and the properties become those of charcoal fuel. Thermally–modified wood has characteristics between those of charcoal and timber (Park and Park, 2011).

In the view of energy efficiency, Bergman reported (2005) that one mass (M) and one energy (E) will retain 0.7 and 0.9 of original mass and energy, respectively, following thermal treatment at 200 to 320°C. Therefore, the thermally–modified wood became 30% lighter, resulting in a 30% higher specific heat of combustion. This is an important property considering the density and thermal efficiency of firewood usability, including thermal efficiency, combustion characteristics, storage, transport, and handling properties (Park *et al*., 2006). Park *et al.* reported (2006) that the relationship between the atomic ratio of Oxygen and Carbon (O/C ratio) and the ratio of Hydrogen and Carbon (H/C ratio) for biomass and various coals are derived from biomass. This highlights the difference between coals and biomass, showing that more carbonized materials have a lower O/C and H/C ratio, and non–carbonized biomasses have a relatively higher oxygen and hydrogen content. Regarding the relationship between element composition and combustion, it is generally recognized that lower levels of oxygen and nitrogen and higher levels of hydrogen and carbon result in a higher caloric value for combustible substances (Park *et al*., 2011).

The purpose of this study is to estimate the effects of thermal pre–treatment on firewood. The Heat Release Rate (HRR), Ignition Time (IT), and Total Heat Released (THR) were measured for each sample to quantify thermal characteristics using a cone calorimeter. An elemental analysis was performed on each test piece using an

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elemental analyzer to characterize and asses the firewood materials for use in auto–camping (Babrauskas V, 1993).

MATERIALS AND METHODS

Testing materials

Timber, charcoal, and thermally–modified wood, as shown in Fig. 1, were prepared from *Quercus variabilis*. These samples were used for experiments and for the estimation of combustion parameters. Wood was thermally–modified during 7 hours with two temperatures, 170°C and 190°C. The charcoal was prepared at the laboratory in the Korea Forest Research Institute.

Component analysis of samples

Air–dried timber, thermally–modified wood, and charcoal were reduced to a powder with a diameter of less than 100 mesh. All the powder was placed in a Falcon Tube and then sealed with Parafilm. An elemental analyzer was used for elemental analysis. Table 1 shows the results from the Elemental Analyzer.

Ignition experiment

The dimensions of the air–dried wood sample, thermally–modified wood, and charcoal specimens are 10 × 10 × 1 cm (width × length × height). The ignition time, Total Heat Release (THR), and Heat Release Rate (HRR) for each test piece was measured using a cone calorimeter. All tests were performed in adherence to the KS F ISO 5660–1 combustion performance test (cone calorimeter method), as shown in Fig. 2.

RESULTS AND DISCUSSION

Higher Heating Value (HHV) analysis based on component analysis

The air–dried timber, thermally–modified wood, and charcoal were respectively ordered in terms of carbonization time. The carbon ratio was increased with thermal modification time because oxygen and hydrogen are released from timber it is thermally modified.

In Table 2, the HHV is the calorie per mass, the formula for which is shown in Formula 1. According to Table 2, charcoal has the highest HHV; however, charcoal has a lower density, which means that it has the lowest value of calorie per volume (Krevelen, 1950).

$$HHV_{fuel} = 0.35C + 1.18H + 0.02N + 0.10S - 0.02A \quad (1)$$

C: Carbon, H: Hydrogen, O: Oxygen, N: Nitrogen, S: Sulfur, A: Ash

Table 3 shows the mass reduction ratio, raw material

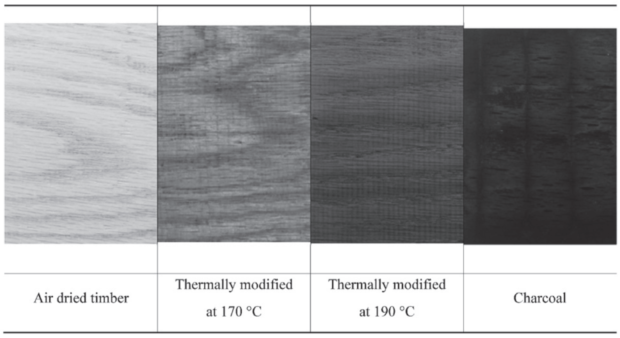

Fig. 1. Experiment specimen (*Quercus variabilis*).

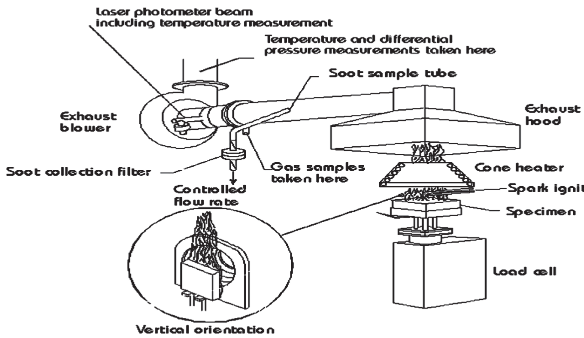

Fig. 2. Schematic apparatus of a cone calorimeter.
Note: Ten Years of Heat Release Research with the Cone Calorimeter by Dr. Vytenis Babrauskas, *Fire Science and Technology Inc*.

Table 1. Condition analysis

Sample Size (mg)	Measuring Range (%)	Injector temperature (°C)	Carrier gas	Carrier gas flow rate (cc/min)	Analysis time (sec)	Detector
0.1~100	0.01~100	1200	He	120	600	TCD

Note : TCD, Thermal Conductivity Dectector

Table 2. Element content and HHV_{fuel}

Samples	Element content (%) [a]				HHV_{fuel} (MJ/kg)
	C	H	O	N	
Quercus variabilis (Air dried timber)	48.9	6.2	44.7	0.3	19.5
Thermally–modified wood 170°C	50.03	5.92	43.90	0.15	21.0
Thermally–modified wood 190°C	53.7	5.6	40.4	0.2	27.3
Charcoal	92.72	0.32	6.37	0.59	32.1

Note: [a], Based on dry weight of samples.

Table 3. HHV_{fuel} according to one ton of material

Samples	Mass loss Rate (%)	Required production mass for 1 ton (Ton)	Produced mass using 1 ton of oak	HHVfuel fuel created by oak 1 ton (MJ)
Quercus variabilis (Air dried timber)	0	1.00	1.0	19,500
Thermally–modified wood 170°C	10	1.11	0.9	18,920
Thermally–modified wood 190°C	20	1.25	0.8	21,840
Charcoal	70	3.33	0.3	9,640

Note: Based on dry weigh of samples; HHV, Higher Heating Values

Table 4. Element ratio

Samples	Ratio		
	O/C	H/C	O/H
Quercus variabilis (Air dried timber)	0.91	0.13	0.139
Thermally–modified wood 170°C	0.88	0.12	0.135
Thermally–modified wood 190°C	0.75	0.10	0.139
Charcoal	0.07	0.00	0.050

Note : O/C, Oxyzen/ Carbon ; H/C, Hydrogen/ Carbon ; O/H, Oxyzen/ Hydrogen

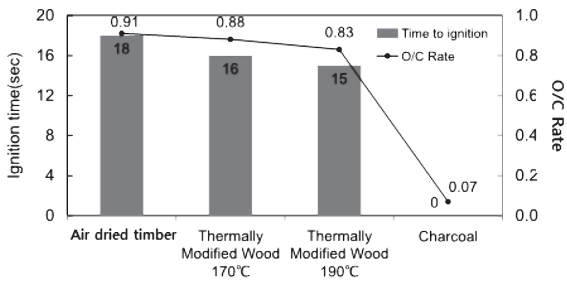

Fig. 3. Ignition time and O/C rate of samples.

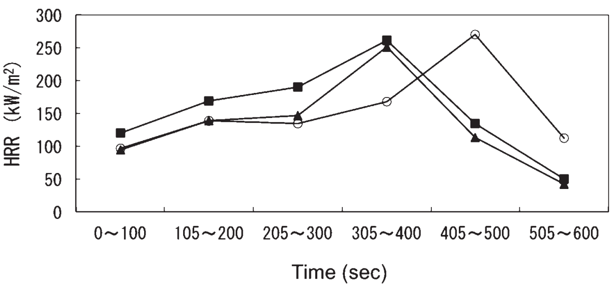

Fig. 4. Per result of mean of HRR range.
Note: Open circles, Quercus variabilis (Air dried timber); solid squares, thermally–modified wood at 170°C; solid triangles, thermally–modified wood at 190°C; HRR, Heat Release Rate

weight for one ton of final product, final product weight from one ton of raw material, and the higher heating value of different substances. While undergoing carbonization, the weight decrease ratio of timber increases, the raw material weight of one ton of final product increases, and the final product weight from one ton of raw material and the higher heating value decreases. As a result, charcoal's higher heating value is the lowest with the same value of raw material, and thermally–modified wood's higher heating value is the same or higher than that of green timber.

Table 4 shows the component element ratio of each test piece. After being carbonized, the O/C, H/C, and O/H ratio decreases.

Ignition experiment result

This study used a 50 kW/m^2 heat flux cone calorimeter for checking ignition time, as shown in Fig. 3, where it can be observed that thermally–modified wood ignites faster than the other test pieces. Furthermore, the ignition time is affected by the element ratio of each test piece. The result of correlation analysis between the test piece's element ratio and ignition time is the correlation coefficient (R) between the O/C rate and ignition time, which has a value of 0.996. According to Fig. 3, reducing the O/C ratio reduces the ignition time; however, charcoal does not ignite because its carbon ratio is high and its oxygen and hydrogen ratio is low, as shown in Table 2. For these reasons, charcoal's calorie for heating is higher than that of the other test pieces. Charcoal does not ignite because the cone calorimeter does not burn enough for charcoal to ignite.

Fig. 4 show the conditional heat release rate (HRR) measured by the cone calorimeter. Table 5 shows the highest heat release rate and the mean heat release rate. Air–dried timber had the maximum heat release rate and was followed by thermally–modified wood and charcoal. 170°C thermally–modified wood had the highest mean heat release rate and was followed by air–dried timber, 190°C thermally–modified wood, and charcoal. However, charcoal did not ignite and only released low heat.

As seen in Fig. 4, all test pieces showed a peak point of heat release rate then decreased. Thermally–modified wood shows the highest heat release rate at the start of ignition when compared with air–dried timber. The thermally–modified wood also reaches peak HRR faster than the air–dried timber. Before 400 seconds, thermally–modified wood showed the highest heat release rate, while the air–dried timber showed the maximum heat release rate at approximately 450 seconds. Because air–dried timber has more moisture than the other test pieces, it has a low heat release rate. Further, thermally–modified wood decreases second maximum combustion point time, because thermally–modified wood has better inside flaming combustion than air–dried timber.

Table 5. Maximum heat release rate and mean heat release rate of samples

Type of sample	Maximum heat release rate (kW/m^2)	Mean heat release rate (kW/m^2)
Quercus variabilis (Air dried timber)	298.86	126.49
Thermally–modified wood 170°C	279.04	126.96
Thermally–modified wood 190°C	296.76	124.11
Charcoal	37.89	26.35

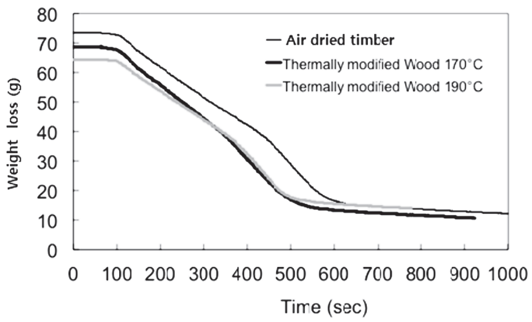

Fig. 5. Mass changing over time for each specimen.

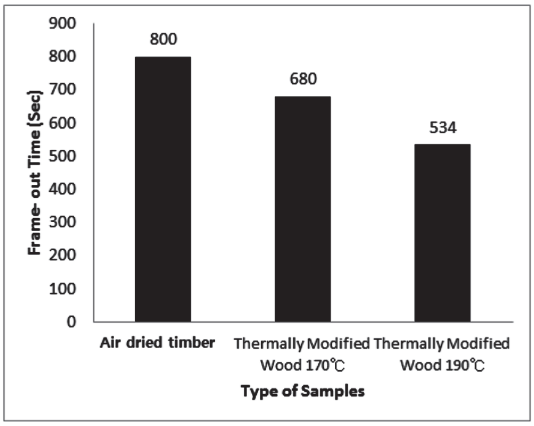

Fig. 6. Time of flame–out of sample.

Charcoal showed the lowest heat release rate because it did not ignite in the cone calorimeter (Park and Park, 2011).

Air–dried timber uses ignition time for the evaporation of moisture from within, and this causes smoke. Thermally–modified wood skips this response, though it has the same HRR as air–dried timber.

Fig. 5 shows the change in mass over time. The mass for each test piece decreases in a constant trend. After the flame–out point, the mass rarely changes. The point at which the mass decreases is the same for all test pieces, though the carbonization time for the thermally–modified wood was shorter than that of the air–dried timber, because the thermally–modified wood has a lower moisture content than that of the air–dried timber, and most of the ignition controlling materials were removed when the timbers were thermally modified. Therefore, thermally–modified wood is an effective camping charcoal, because it is able to decrease the time taken to change to charcoal.

Flame–out is the time between ignition and when a fire goes out. Fig. 6 shows that the flame–out of the 170°C thermally–modified wood is shorter than that of the air–dried timber. According to Fig. 4, the mass decreasing ratio becomes smaller after 500 seconds when all 3 of the test pieces are burning. This means that all test pieces lost their firewood function and remained as charcoal.

Shorter flame–out time firewood is able to remain as charcoal longer; therefore, thermally–modified wood is a better auto camping site ignition charcoal than air–dried timber.

CONCLUSION

To estimate the heating efficiency of 170°C thermally–modified wood for use as camping charcoal based on carbonization, 190°C thermally–modified wood, charcoal, and air–dried timber were analyzed via an elemental analyzer, and a cone calorimeter. The results are as follows:

In process carbonizing, the ratio of carbon to nitrogen increases while that of hydrogen to oxygen decreases.

The ignition time of thermally–modified wood is faster than that of air–dried timber, though the charcoal does not ignite.

The HRR of air–dried timber is the highest, because air–dried timber does not lose mass per unit while being thermally modified, and therefore has a high potential calorie count.

With the exception of charcoal, all test pieces show the same HRR trend. Thermally–modified wood has higher initial HRR than air–dried timber because thermally–modified wood ignites faster than air–dried timber. Also thermally–modified wood has better inside flaming combustion when compared to air–dried wood so it reaches a second HRR point faster.

Expect charcoal, all test pieces show the same trend in decreasing mass.

The Flame–out time for carbonized charcoal time is shorter, and it remains as charcoal longer than the others.

Thermally–modified wood's ignition time is fast, and HRR is high; therefore, thermally–modified wood is suitable for camping charcoal.

ACKNOWLEDGEMENTS

This work was supported by a grant (S211313L010140) from the Forest Science & Technology Projects, Forest Service, Republic of Korea.

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