# Combustion and Thermal Characteristics of Korean Wood Species

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This study examined the combustion and thermal characteristics of domestic wood species in Korea. Wood was tested using a cone calorimeter according to the KS F ISO 5660-1 (2003) standard. The combustion properties of the wood were measured in terms of the heat release rate (HRR), total heat released (THR), mass lose rate (MLR), and ignition time (time to ignition; TTI). An optical microscope was used to determine the anatomical characteristics of wood. Also, the thermal properties were measured using thermogravimetric analysis (TGA) to determine the thermal stability of wood. The results of this experiment could be useful for fundamentals of guiding the combustion properties and thermal stability when using wood for various applications.

*Keywords: Combustion properties; Domestic wood; Cone calorimeter; Heat release rate; Mass loss rate; Thermogravimetric analysis*

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## INTRODUCTION

Wood has various beneficial properties, *e.g.*, it is environmentally friendly, sustainable, renewable, and mechanically strong. It is widely used for construction and furniture materials. The demand for wood applications in residential and commercial building construction has increased in recent years. However, when used as a construction material, wood is limited because of its flammability (Grexa and Lübke 2001; Lee *et al*. 2011; Seo *et al*. 2013, 2015; Lowden and Hull 2013).

Wood is composed of three main components (cellulose 22% to 29%, hemicellulose approximately 40%, and lignin 28% to 35%); these components are organic materials. All three components begin thermal decomposition at a temperature of approximately 200 °C. The temperature range for generating volatilized gases from the thermal decomposition temperature for the respective components is as follows: cellulose 250 to 400 °C, hemicellulose 200 to 300 °C, and lignin 280 to 500 °C (Yang *et al*. 2006; Chung and Spearpoint 2007; Lowden and Hull 2013; Son and Kang 2014). The complex chemical reactions during thermal decomposition processes form char, accompanying the changes in the heat and weight of materials. Lignin in wood is an amorphous polyphenolic plant constituent; its chemical structure (aromatic ring) is able to give a very high char yield, which can still reach 35% to 38% at 900 °C. Also, Hosoya *et al.* (2006) and Garcia-Perez *et al*. (2008) reported that lignin has the best heat-resistance (Hosoya *et al*. 2006; Garcia-Perez *et al*. 2008; Pelasz-Samaniego *et al*. 2014; Xing and Li 2014). When the heat source is applied to the wood, it produces a variety of combustion gases. The flammable gases are induced to ignition on the surface of wood by adding air. Another important characteristic in the combustion process for wood is the heat release rate (HRR). The HRR data efficiently assesses the relative heat contribution of materials according to the conditions of the material, such as thick, thin, untreated, or treated, under fire exposure (Delichatsios *et al*. 2003; White and Dietenberger 2010; Lowden and Hull 2013; Rabaçal *et al*. 2013).

In case of fire, the combustion and thermal properties of wood applied in buildings can be evaluated by applying elements such as the heat release rate, ignition time, and propagation velocity on the materials surface (KS F ISO 5660-1 2003); Gratkowski *et al*. 2006; Mouritz *et al*. 2006; White and Dietenberger 2010; Lee *et al*. 2011; Rabaçal *et al*. 2013). Heat release rate (HRR), total heat released (THR), and time to ignition (TTI) can be measured using a cone calorimeter, which can measure the heat release rate by utilizing the principle that oxygen is consumed during the burning times (KS F ISO 5660-1 2003). Thus, a cone calorimeter was used to measure various combustion characteristics for six domestic wood species (Red pine, Japanese larch, Japanese cedar, Manchurian Ash, Korean fir, and Giant dogwood) used for building construction in Korea.

The wood species were observed using an optical microscope to confirm the unique anatomical characteristics of each species. An optical microscope is widely used to observe wood specimens because it creates a magnified image of an object and magnifies the image to allow the user to analyze it.

The internal structures of each species were observed using this principle to distinguish any anatomical characteristics of the wood that could affect the combustion characteristics. Also, thermogravimetric analysis (TGA) was used for measuring the thermal stability and other properties, such as mass lose rate and thermal decomposition temperature of the wood species (Yang and Roy 1999; Kim *et al*. 2014). TGA is measured by adding the specimens to mass changing of the specimens according to the change of temperature rising as a function (Yang and Roy 1999; Kim *et al*. 2014; Seo *et al*. 2015). The TGA test was performed to determine the mass loss rate of the different wood species at temperatures ranging from 20 to 800 °C.

The aim of this research was to determine the combustion properties of domestic woods according to KS F ISO 5660-1 (2003), using a cone calorimeter. Also, the purpose of this study is to assess the thermal properties of domestic woods for use in building and furniture materials. TGA was used to determine the thermal behavior.

## EXPERIMENTAL

### Materials

In this experiment, six kinds of domestic wood species were used: red pine (*Pinus densiflora*), Japanese larch (*Larix kaempferi*), Japanese cedar (*Cryptomeria japonica*), Manchurian ash (*Fraxinus mandshurica*), Korean fir (*Abies koreana*), and giant dogwood (*Cornus controversa*). These wood species are commonly used for building and construction materials in Korea (Lee and Kim 2013). For testing with the cone calorimeter, the wooden specimens were sized at 100 mm × 100 × mm × 10 mm, according to KS F ISO 5660-1 (2003).

Test specimens are presented in Fig. 1, and the physical properties of specimens are shown in Table 1.

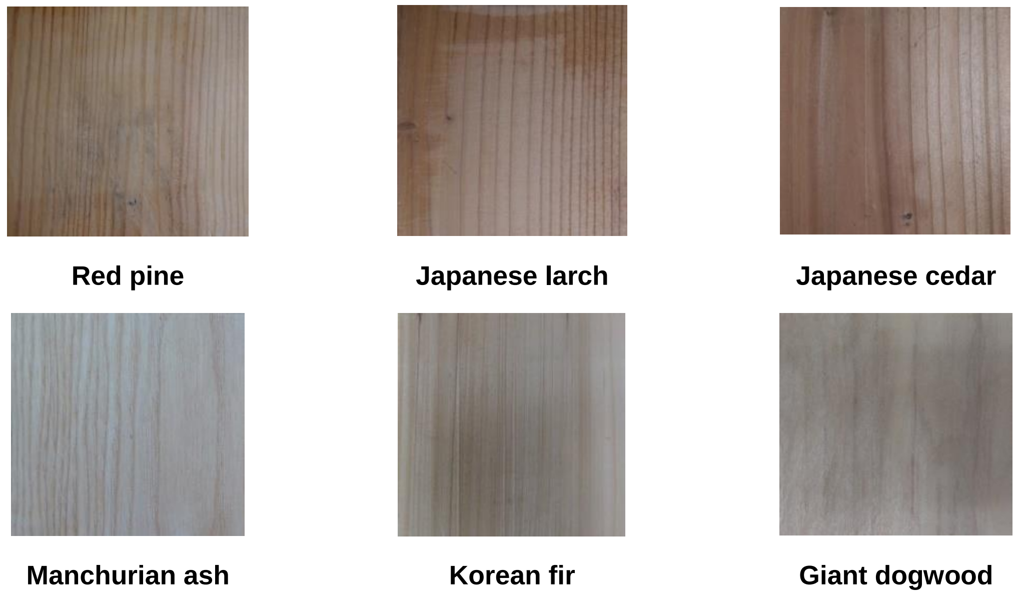


**Fig. 1.** Testing design of wood

**Table 1.** Density of the Specimens

| Specification | Red pine | Japanese larch | Japanese cedar | Manchurian Ash | Korean fir | Giant dogwood |
|---|---|---|---|---|---|---|
| Mass (g) | 53.76 | 48.58 | 32.65 | 68.80 | 34.75 | 58.10 |
| Density (kg/m$^2$) | 0.54 | 0.46 | 0.31 | 0.70 | 0.32 | 0.59 |

For optical microscopy, the specimens were produced after visually confirming the third section (transverse section, radial section, tangential section) of the wood. Identified specimens were cut in the form of blocks 5 mm × 5 mm × 5 mm. The blocks were composed of flakes of size 15 to 20 μm using a sliding microtome to measure each section.

## Methods

*Optical microscopy*

Optical microscopy (Carl Zeiss, DE/Axio Imager M1) was carried out to confirm the anatomical characteristics of the species. The flake woods were stained by safranin, then dehydrated with ethanol, and produced by the permanent preparates. Completed permanent preparates were observed and photographed, confirming the internal structure of the wood.

*Cone calorimeter test*

The cone calorimeter test was carried out according to KS F ISO 5660-1 (2003). The woods were conditioned to stabilization at 50% and 25 °C prior to testing. The experiments were conducted by placing the woods in the same holder in a horizontal position under the cone heater. The wooden specimens were heated with a heat flux of 50 kW/m$^2$. Before the test, wooden specimens were maintained at temperature 25±2 °C and a relative humidity of 50±5%. Figure 2 shows the cone calorimeter (Fire Testing Technology Ltd, UK) used in this experiment.

**Fig. 2.** Cone calorimeter

*Thermogravimetric analysis (TGA)*

The TGA (TA Instruments Inc., 2960 SDT, USA) was carried out to confirm the thermal properties of the wood. The differential thermal (DT) analysis method is a technique similar to differential scanning calorimetry. It has been used to determine the enthalpy change and mass loss of specimens (Yang and Roy 1999; Seo *et al*. 2015). The thermal degradation of the wood was measured under nitrogen flow in a range of 25 to 800 °C at a heating rate of 20 °C/min. Wood was milled to sizes of 100 to 120 mesh for this experiment.

## RESULTS AND DISCUSSION

### Combustion Properties

The combustion properties of six kinds of domestic wood species were estimated by cone calorimeter tests. During the experiment, the following parameters were determined: heat release rate (HRR), peak heat release rate (PHRR), total heat release (THR), and mass loss rate (MLR). In addition, CO and $CO_2$ gas emissions by each specimen were measured to determine the correlation between gas release and burning of the materials.

*Heat release rate (HRR)*

The HRR is a very important parameter for evaluating the fire characteristics of wood (Grexa and Lübke 2001; Lee *et al*. 2011). It represents the number of calories released by the surface area of the materials. Also, it is the best indicator of the risk associated with material burnings (Grexa and Lübke 2001; Seo *et al*. 2015). Figure 3 shows the HRR curves.

The HRR curve shapes typically show two peaks. Generally, the first peak results from char formation by carbonization in the surface of the wood (Pelasz-Samaniego *et al*. 2014; Son and Kang 2014). According to a report by Yang *et al.* (2003), the surface and inner temperature of wood increase with external heat flux. After that, wood pyrolysis begins to increase and char is formed on the surface of wood (Yang *et al*. 2003). As shown in the graph, the temperature range of the first peak was similar among the all the wood species. It was also similar to the thermal decomposition temperature of hemicellulose in progressing char formation. The second peak of the HRR curve corresponds to the gradual burning of the woods through the char layer. Grexa and Lübke (2001) report that this peak is unique and indicates the heat release rate of all wood. Table 2 shows the results of the cone calorimeter test.

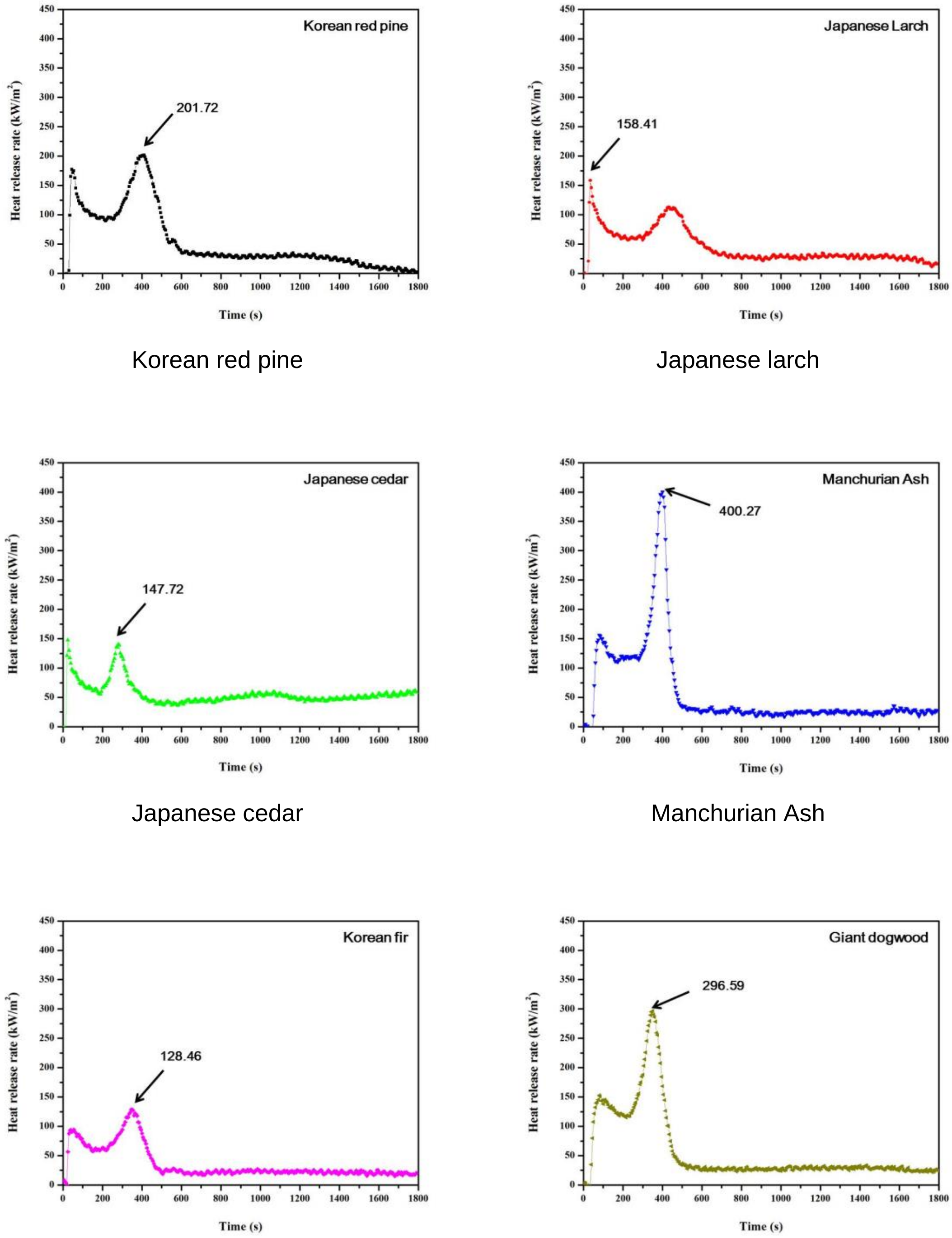


**Fig. 3.** HRR as a function of time for domestic wood

**Table 2.** Results of Cone Calorimeter Test

| Parameter | Red pine | Japanese larch | Japanese cedar | Manchurian ash | Korean fir | Giant dogwood |
|---|---|---|---|---|---|---|
| PHRR ($kW/m^2$) | 201.72 | 158.41 | 147.72 | 400.27 | 128.46 | 296.59 |
| THR ($MJ/m^2$) | 95.39 | 79.53 | 73.84 | 102.95 | 64.81 | 103.06 |
| CO mean (kg/kg) | 0.053 | 0.089 | 0.092 | 0.055 | 0.103 | 0.058 |
| $CO_2$ mean (kg/kg) | 2.275 | 2.272 | 2.289 | 2.146 | 2.790 | 2.052 |
| $CO/CO_2$ | 0.023 | 0.039 | 0.040 | 0.026 | 0.037 | 0.028 |
| Time to ignition (s) | 24 | 18 | 9 | 40 | 19 | 33 |
| Mass loss rate (%) | 98.12 | 96.61 | 99.83 | 90.62 | 92.31 | 95.15 |

The peak of heat release rate (PHRR) value is considered an important parameter that best expresses maximum intensity of HRR (Xu *et al*. 2015). The confirmed PHRR values of woods were as follows: red pine 201.72 $kW/m^2$; Japanese larch 158.41 $kW/m^2$; Japanese cedar 147.72 $kW/m^2$; Manchurian ash 400.27 $kW/m^2$; Korean fir 128.46 $kW/m^2$; and giant dogwood 296.59 $kW/m^2$. The highest PHRR value was obtained for Manchurian ash, possibly because Manchurian ash is composed of a high density compared to other species.

As indicated in the graph, the calories in hardwoods (Manchurian ash and giant dogwood) were higher than in softwoods (red pine, Japanese larch, Japanese cedar, and Korean fir). Also, it was confirmed that the time to ignition was faster for softwoods than hardwoods. Wood is a porous material, so the emitted heat from the flame can be absorbed into the pores and pits of the wood (Evans 1991). Seo *et al*. (2015) and Kim and Drzal (2009) reported that an endothermic reaction can occur in the pores of the porous materials. It was determined that the pores of hardwoods are bigger than those of softwoods, and on the basis of microphotographic images. Materials with a high specific surface area showed that the heat absorbing reaction occurred between the pores (Fig. 4). Additionally, Lorenzetti *et al*. (2013) and Chen *et al*. (2013) reported that external heat can be absorbed into the pores of porous materials and that heat was measured at the time of the thermal analysis of the materials.

In the case of hardwoods, the extractives contained in the pores were thought to affect the time to ignition of the woods. Manchurian ash had the highest density and initial mass, and the residual rate of mass reduction was low compared with other species. This result also meant that a large amount of char formed from the extractives. Xing and Li (2014) reported that the char of hardwoods is harder than that of the softwoods, while Xu *et al*. (2015) reported that the rate of char differed depending on the species and density of woods. In this experiment, similar results compared with previous studies were confirmed.

Time to ignition (TTI) is an important parameter for evaluating the fire characteristics and flammability of materials (Li 2003; Lee *et al*. 2011). Figure 5 shows the TTI of the wood species. The TTI of Manchurian ash was the longest. It is proposed that this is because Manchurian ash has wider pores compared to the other species. Romagnosi *et al.* (2013) reported that the heat absorbing characteristics of the materials is due to pores within the materials.

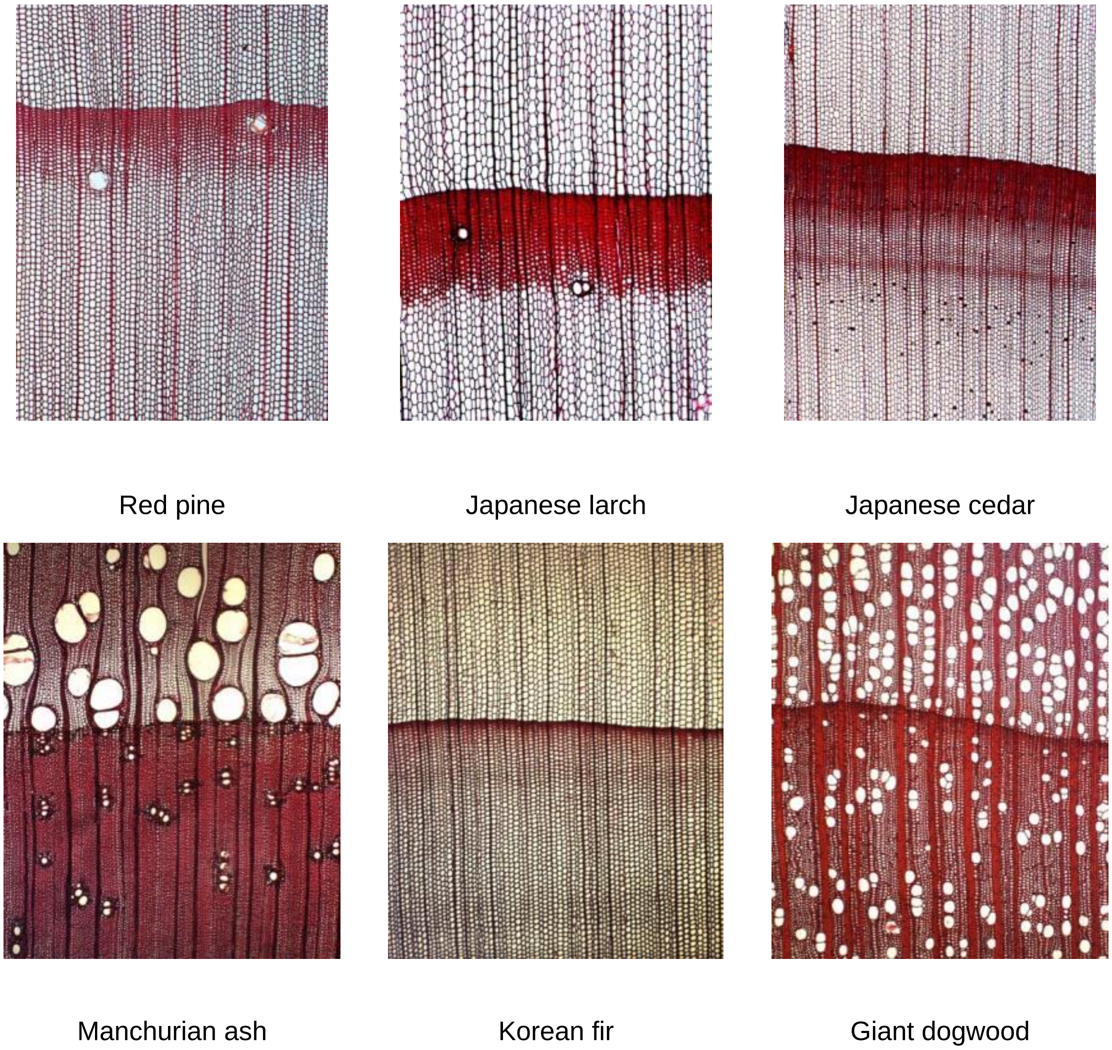


**Fig. 4.** Micrograph images of wood species (cross-section)

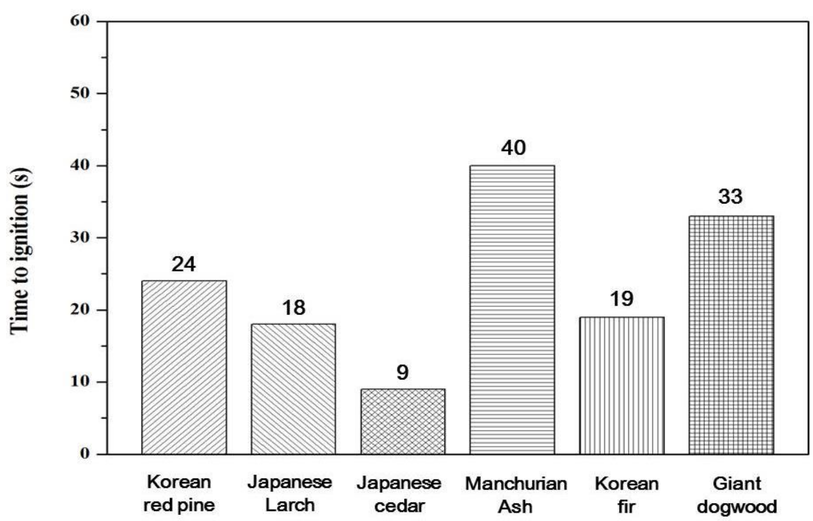


**Fig. 5.** TTI of the wood species

The results suggest that the pores in the specimens caused an endothermic reaction, so that time to ignition was delayed on the surface of that species. Among the softwoods, the TTI of Japanese cedar was confirmed to be the shortest. Generally, softwood species possess resin canals containing a variable amount of resin. Hardwood species, however, have oil cells or crystalliferous cells containing crystal and silica (Boonstra *et al*. 2006; Kim and Kwon 2009). It was determined that the inclusions in the hardwoods affect the TTI of woods so that ignition is delayed compared with softwood.

*Total heat release (THR)*

The total heat release (THR) is the total amount of heat released during the combustion, emitted from the surface of the materials.

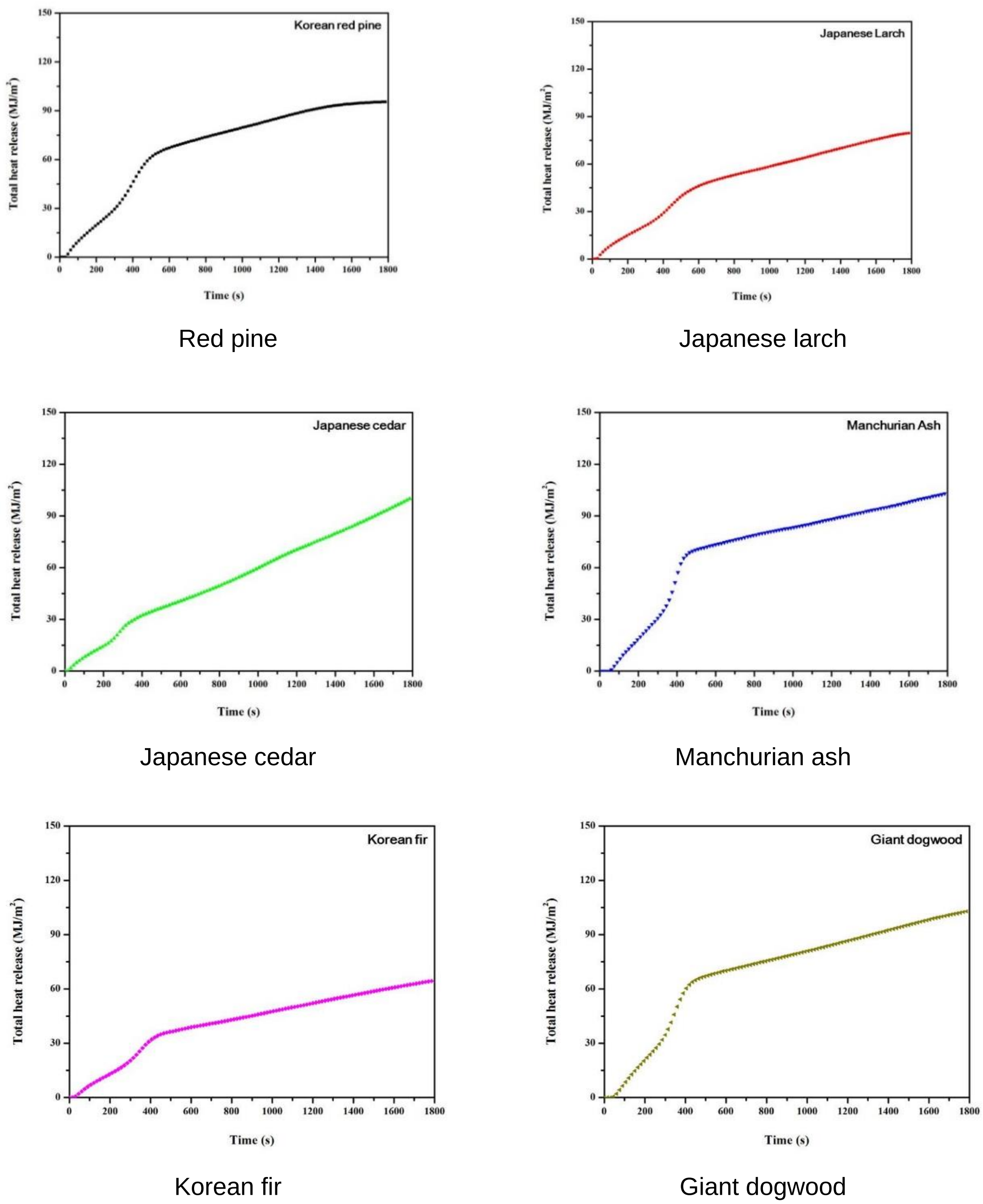


**Fig. 6.** THR as the function of time for domestic wood

It is important to explain the potential for flame spread when a fire occurs (Grexa and Lübke 2001; Lee *et al*. 2011; Seo *et al*. 2015). Figure 6 shows the THR curve after the cone calorimeter test. As shown in the graphs, the THR curves exhibited a tendency similar to the results of HRR, and the highest content was in the Manchurian ash. Because Manchurian ash is wide ring porous, the species has high heat absorption capacity (Chung and Spearpoint 2007; White and Dietenberger 2010). Chung and Spearpoint (2007) reported that the hardwoods had high carbon content and would generate more heat than softwoods. This affected the HRR and THR value. The results of this experiment showed a trend similar to the previous research.

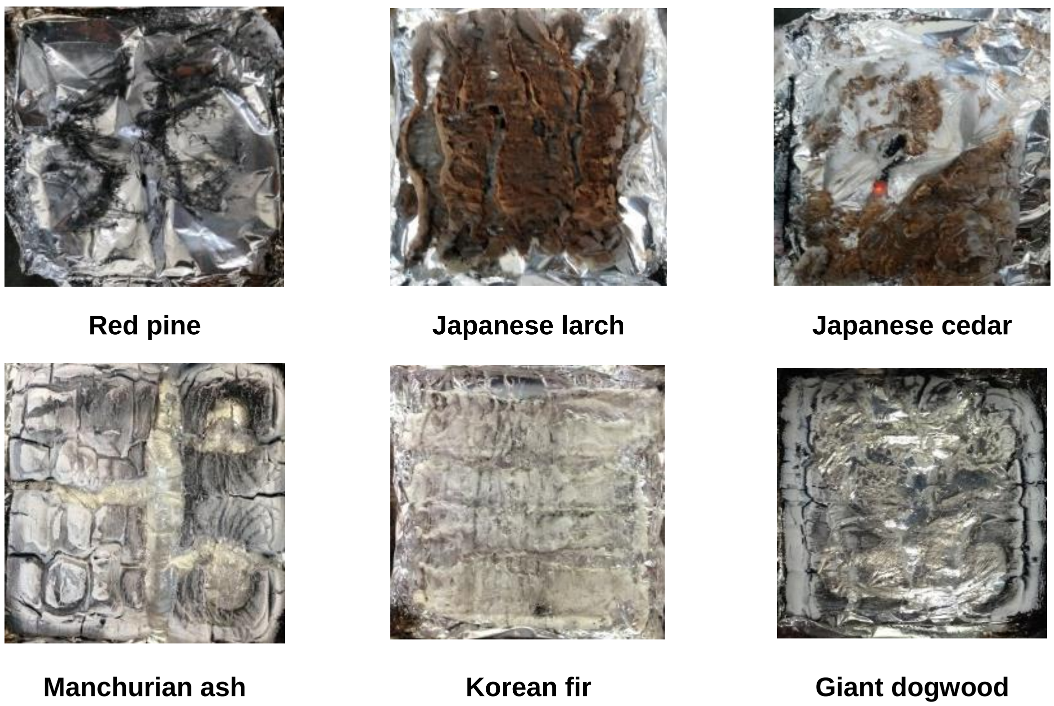


**Fig. 7.** Wood specimens after the cone calorimeter test

Figure 7 shows the test specimens after the cone calorimeter test, with the remaining ash after combustion of wood species respectively. The ash remaining after incineration of red pine, Manchurian ash, Korean fir, and Giant dogwood showed gray color. However, for Japanese larch and Japanese the ash specimens were dark brown. These differences must be attributable to the unique properties of components in wood species. However, addition research will be needed in order to account for ash color based on various chemical components of the wood.

*Thermal properties*

Thermal properties were measured by thermogravimetric analysis, which was conducted to determine the mass change in wood by the temperature increasing over time (Yang and Roy 1999; Chen *et al.* 2013; Zhang *et al.* 2014).

The TGA of an ideal composition was used to analyze substances such as volatile components (water, solvents), polymers, carbon-containing components, and ash (Seo *et al*. 2013). Figure 8 shows the thermal degradation behaviors.

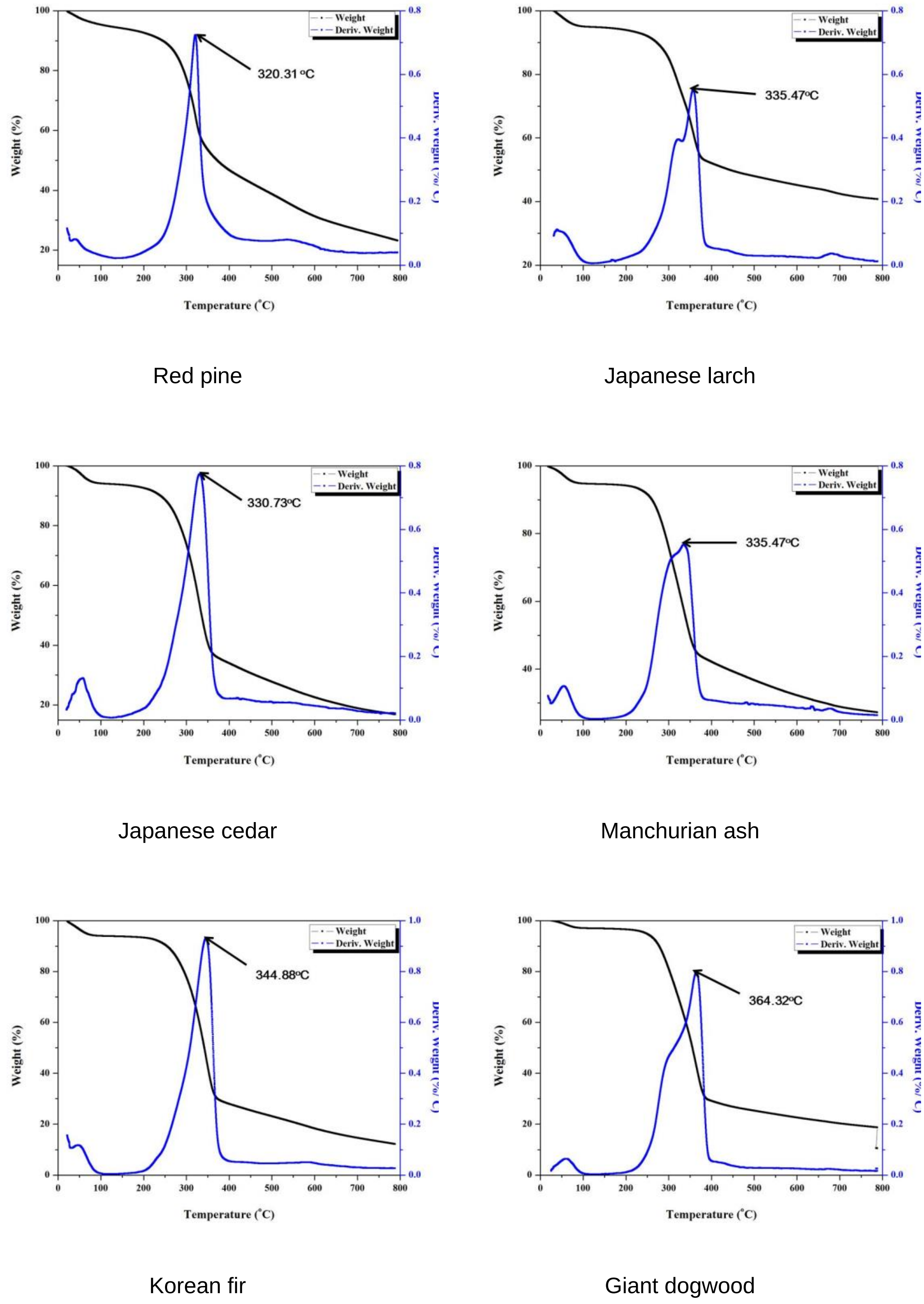


**Fig. 8.** TG-DTG analysis as a function of time for domestic wood

All wood specimens exhibited degradation of cellulose that began at the temperature range of 200 to 250 °C. A peak in the first range indicated the gasification of moisture in the wood (Almeida *et al*. 2008; Fujii *et al*. 2011; Xing and Li 2014). Randriamanantena *et al*. (2009) reported that the peak in the second range represents a unique thermal decomposition temperature of the species. Thermal decomposition temperatures of the woods by TGA were recorded as 320.31 °C for red pine, 335.47 °C for Japanese larch, 330.73 °C for Japanese cedar, 335.47 °C for Manchurian ash, 344.88 °C for Korean fir, and 364.32 °C for giant dogwood. These findings suggest that the thermal decomposition of cellulose and hemicellulose woods is in progress in earnest starting at temperatures in the range 300 to 400 °C (Seo *et al*. 2013; Zhang *et al.* 2014).

The effect of heating rate on weight loss rate (DTG) means the starting point of char formation or pyrolysis on the materials. Approximately 41.62 °C, red pine starts to form char. In the case of pyrolysis of Japanese larch, it began at approximately 58.17 °C. Also, Japanese cedar was 56.79 °C, Manchurian ash was 54.89 °C, Korean fir was 48.08 °C, and giant dogwood was 61.06 °C starting pyrolysis respectively. In addition, the peak of curve appears between 300 °C and 360 °C in all species. In this temperature range, pyrolysis of red pine proceeded radically. The period of char of the materials to be broken was also in this temperature range.

## CONCLUSIONS

In this study, the combustion properties of domestic woods were investigated according to KS F ISO 5660-1 (2003) using a cone calorimeter. Thermal properties were measured by thermogravimetric analysis. The aim of this study was to provide basic information about domestic woods for the database of research for improving fire safety. A tendency was noted that the peak of heat release rate of the hardwood appeared at higher temperature than that of softwood. However, in the thermogravimetric analysis, it showed a similar tendency to the pyrolysis properties of the five kinds of species.

1. A cone calorimeter test was conducted to determine the combustion characteristics of domestic woods. The maximum PHRR was shown to be 400.27 kW/m$^2$ for Manchurian ash. The minimum PHRR was confirmed to be 128.46 kW/m$^2$ for Korean fir. In the case of THR, the highest value measured was for giant dogwood, at 103.06 MJ/m$^2$. The lowest value of THR was confirmed for Korean fir, at 64.81 MJ/m$^2$. Based on these results, it was determined that the HRR and THR were associated.
2. The TTI of Manchurian ash was the longest of all the woods, and that of Japanese cedar was confirmed to be the shortest. PHRR, TTI, and THR are all associated with each other, and they are capable of determining the fire hazard and possibility of fire spread.
3. The thermal decomposition temperature of domestic woods measured by TGA are as follows: red pine 320.31 °C, Japanese larch 335.47 °C, Japanese cedar 330.73 °C, Manchurian ash 335.47 °C, Korean fir 344.88 °C, and giant dogwood 364.32 °C.

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