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A Study on the Combustion of Living Leaves of Abors for Crown Fire Identification in Korean Warm Temperate Forest Zone

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This study used Auto Ignition Temperature Tester (KRS–RG–9000) and Dual Cone Calorimeter(ISO 5660–1) in 14 representative species of trees as part of research on the fire watch of crown fire in the formed tree of sub–tropical forest and considered the initial combustion characteristics such as ignition characteristics and heat generation characteristics and fire load. In the green leaf, the percentage of moisture content was 116~248%, which differed according to the species of trees and the *Daphniphyllum macropodum* which showed the highest percentage of water content, which was 2.14 times more than the *Abies koreana* Wilson which showed the lowest percentage of moisture content.

Flameless igniting temperature was 251~383°C and *Quercus serrata* and *Carpinus tschonoskii* showed a relatively lower flameless igniting temperature, and the flameless igniting temperature of *Carpinus tschonoskii* was 61°C, which showed the shorted time than the other species of trees. Both total heat release and mean heat release rate showed the highest values in six species of trees such as yew, *Taxus cuspidata, Prunus maximowiczii, Betula ermani var. communis, Carpinus tschonoskii, Acer palmatum*, and *Acer pseudo–sieboldianum*. Based on these findings, a colony of yew, *Taxus cuspidata, Prunus maximowiczii, Betula ermani var. communis, Carpinus tschonoskii, Acer palmatum,* and *Acer pseudo–sieboldianum* has a high fire load according to the high heat generation rate when its crown fire proceeds and the fire strength is expected to be big, and as *Carpinus* tschonoskii has a high risk of ignition, it is considered that its fire spread will proceed rapidly on forest fire.

Key words: forest fire, crown fire, warm temperature zone

INTRODUCTION

Like general fire, forest fire is caused by fuel, oxygen, and heat, but it happens in complex and various forms like the types of forest floor, an array of fuels, and density and geomorphic effects such as climate and winds (Davis *et al*., 1959). In Korea, about 78% of the total annual number of forest fire occurs in March to May in which the relative humidity is the lowest, and on forest fire, fire spread and propagation shows a high risk of fires caused by relative humidity and various forms and patterns of fire according to the types and forms of forest fuels (Lee Si–Young *et al*., 2001; Whelan 1995; Bond and van Wilgen 1996; Carrington and Keeley 1999; National Forestry Administration, 1998). The risk of fires by the relative humidity is as follows:

- If the relative humidity is more than 60%, fires are almost impossible.
- If the relative humidity is 50~60%, forest fire burn slowly or anything that is easy to be burned is burned.
- If the relative humidity is 40~50%, fire does not spread to a wide area.
- If the relative humidity is 30~40%, there is a risk of rapid combustion by a considerable flame.
- If the relative humidity is 25~30%, it burns rapidly and there are times when the fire is difficult to be put out.
- If the relative humidity is less than 25%, crown fire occurs.

Bush fire depends on such a relative humidity, vapour concentration of combustibles, size, density, array, and temperature of combustibles (NFPA, 2011), and the types of bush fire are classified according to the part of damage: underground fire that burns the humus layer in the ground; surface fire that burns weeds, shrubs, and fallen leaves on the surface of the earth; crown fire that burns the branches and leaves on a standing tree; stem fire that burns the stems of a standing tree. In most cases, forest fires start from surface fire and spreads gradually to crown fire and underground fire, and if surface fire, underground fire, stem fire, and crown fire are all proceed and done, it is difficult to put out the forest fire at the initiatory stage. In addition, when the fires had gone through surface fire, underground fire, stem fire, and crown fire, the fires are difficult to be put out within a short time effectively due to land features, water supply,

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equipment, mobilization, and other bad conditions and in most cases it spread to a wide area. So, proactive measures to this are above all important (Gang Jeon–Yu *et al.*, 2002).

For an effective measure to prevent forest fires, the first thing to do is to investigate the events and accidents related to fires and the causes thoroughly. In an investigation on the events and accidents related to forest fires, cause of fires, causes of fire spread, reasons of failure in the initial combustion, and causes of human victims should be investigated. In addition, the investigation of fire causes is not only to reveal the origin of a fire but also to reveal the process from the source of fire to the point of extinguishing the fire and identify the causes of fire outbreak, factor of fire spread, cause of occurrence of casualties, etc. The investigation of causes of fire outbreak is to determine the parts of fire outbreak, to identify the source of ignition existed on the part of fire outbreak, and to verify the process of fire outbreak such as course of ignition scientifically, and the investigation of fire spread is to reveal the whole process from the fire outbreak to the fire extinction. In addition, the investigation of causes of human victims is to observe the relations of fire with physical and personnel environment– combustibles and evacuation– in relation to the causes of fire outbreak and causes of fire spread (Sin Dong–So *et al.*, 1994).

In the research of fires, it is not easy to collect data in the field, and it is also difficult to identify the initial combustion characteristics exactly as the combustion environments are so complex. Therefore, this study aims to consider the thermal characteristics and fire load characteristics necessary for the analysis of path of crown fire and combustion pattern in the species of trees of sub–tropical forest in Korea.

THEORETICAL BACKGROUNDS

1. Fire Pattern

In case of investigation of point of ignition of forest fire, combustion pattern should be used carefully. Combustion pattern is a part of fire pattern, and so for an exact understanding of this, the ability to interpret the fire pattern is required. The ability to interpret the fire pattern exactly is an essential factor to reproduce the fire field, and as the fire pattern is also visible evidence that still remains after fire becomes extinct, it is very important to evaluate the fire damage and determine the part of fire source to analyze such fire patterns. In addition, heat transfer, flame spread, and flame spread are major factors to the changes in the exposed surface and appearance of materials during the period of fire (Lee Chang–Uk, 2007).

Diffusion velocity differs significantly according to the vertical combustion and horizontal combustion. In horizontal combustion, pre heating and thermal cracking by radiant heat occur at the combustible area around the flame, and the horizontal combustion is so slow than the vertical combustion. In vertical combustion, the combustion speed in the direction of upward the ignition point than in the horizontal direction or downward direction when there occurs a fire on the central point of vertical combustibles, and in the upper part of ignition point, combustibles are pre heated by hot air before flame reaches it. In the direction of fire upward, the combustion speed is about 20 times faster than the horizontal direction (Lee Seung–Hun, 2009).

2. Crown Fire–Fire Identification

When the actual wildfires occur, four kinds of fires such as surface fire, stem fire, crown fire, and underground fire can occur simultaneously. In the geographical features of Korea, the slope is so steep and there are so many hill areas, and the water storage is not big. So most of wildfires start from surface fire at the bottom part of a mountain, but leads to crown fire at the top of a mountain (Gang Jeon–Yu *et al.*, 1997). Crown fire is caused by surface fire and the force of a fire spreads from stem fire to crown fire. So forest trees wither by the heat. This event often occurs in a coniferous forest: pine tree and cedar tree. The fuels for crown fire are branches and leaves, and to interpret the crown fire's route of occurrence and combustion pattern, its thermal characteristics should identified first.

3. Major Species of Trees Depending on Climate

In the climate of Korea, it is cold and dry in the winter, and it rains intensively in the summer. Such a unique rainfall pattern is characteristic of temperature monsoon climate. In addition, the climate area is classified into warm temperate of rest, temperate forest, and freezing forest zone. Horizontally, a wide variety of natural vegetation can be observed from warm temperate zone and temperate climate region in the south to the polar region in the north. Vertically, a wide variety of natural vegetation can be observed from the lowland with low sea level altitude to the alpine district with high sea level (Lee Byeong–Du *et al.*, 2005). The species of tress to the climate zone of Korea are shown in Table 1.

EXPERIMENTAL METHODS

1. Specimen Selection

In this study, we collected green leaves from 14 species of wood forest distributed in the warm temperate forest zone and selected them for experimental fuels, which are shown in Table 2. The fuels were collected three times on the next day when a fine day lasts for five days or more from September to October in order to apply the same conditions for the period of fuel collection, and the types of specimen were used in the original form to apply the same types and conditions for fuels on forest fire actually.

2. Experimental Methods

2.1 Moisture Content Measurement

The percentage of moisture content was quantified at an amount of 200 g by ASTM D 2016(American Society for Testing and Material) method (Kim Hyun–Jung *et al.*, 2004), the weight was measured and calculated until

Table 1. The Korean Distributional Species of Trees by Climatic Zone

		Special species of trees	Species of trees for reforestation	Regions
Temperate forest zone	southern part	*Cephalotaxus koreana NAKAI, Bam busoideae, Antipathes japonica Brook, Lindera eryghrocarpa Makino, Zanthoxylum schinifolium S. et Z., Euonymus japonica Thunb., Platycarya strobilacea Siebold & Zucc. var. strobilacea for. strobilacea, Celtis sinensis Pers., Euonymus fortunei var.radicans(Sieb et Miq.)Rehder, Camellia 'Tomorrow's Dawn', Zanthoxylum planispinum S. et Z., Acer palmatum Thunb., Carpinus tschonoskii MAX., Carpinus laxiflora Bl., Pinus densiflora S. et Z. et al.*	*Pinus densiflora S. et Z., Larix olgensis var. koreana (Nakai) Nakai, Larix leptolepis, Pinus koraiensis S. et Z., Antipathes japonica Brook, Abies holophylla MAX., Ginkgo biloba, Castanea crenata, Quercus acutissima CARRUTH , Quercus variabilis Blume, Quercus dentata Thunb. ex Murray, Zelkova serrata MAKINO, Juglans sinensis, Rhus verniciflura, P. coreana, Acacia decurrents var. dealbata, Alnus japonica (Thunb.) Steud., Populus deltoides, Cornus kousa F. Buerger ex Miquel, Fraxinus mandshurica Rupr., Fraxinus rhynchophylla Hance, B. schmidtii, Bam busoideae, Pinus rigida Mill. et al.*	A zone from the end of warm temperate to latitude 38° in the eastern part (south of Gang Reung), 37° to the western part (south of the central part of Chungnam)
	middle part	*Styrax japonicus Siebold & Zucc, Quercus xmccormickii Carruth, Quercus mongolica, Juniperus chinensis L., Abies holophylla MAX., B. schmidtii, Pinus densiflora S. et Z. et al.*		A zone to latitude 40° in the eastern coast(south of the central part of Hamnam), 38° in the central district(three islands in Gangwondo, Hwanghaedo), 39° in the western coast(south of the central part of Pyeongnam)
	northern part	*Tilia amurersis, B. schmidtii, Quercus mongolica, Betula costata Trautvetter, Acer komarovii Pojark, Acer tegmeutosum MAX., Syringa patula var. kamibayshii (Nakai) K. Kim, Pinus koraiensis S. et Z., Abies holophylla MAX., Larix olgensis var. koreana (Nakai) Nakai et al.*		A zone of areas excluding the highlands of Pyeongando, Hamgyeongdo in the north of central part of temperate climate regions
Warm temperate forest zone		*Viburnum awabuki K. Koch, Melia azedarach var. japonica MAKINO, Ternstroemia japonica, Cinnamomum camphora Sieb., Cinnamomum japonicum Siebold, Camellia japonica L., Cleyera japonica Thunb., Euonymus japonica Thunb., Quercus acuta Thunb. ex Murray for. acuta, Quercus myrsinaefolia Bl., Quercus salicina, Pittosporum tobira (Thunb.) W. T. Aiton, Ilex integra, Machilus thunbergii, V. bracteatum, Castanopsis cuspidata var. sieboldii Nakai, Aucuba japonica, Prunus maximowiczii Rupr., Betula ermanii var. subcordata, Abies koreana E.H. Wilson, Quercus mongolica, Carpinus tschonoskii MAX., Daphniphyllum macropodum Miq., Carpinus laxiflora Bl., Prunus sargentii REHDER, Acer palmatum Thunb., Styrax japonicus Siebold & Zucc, Acer pseudosieboldianum (Pax) Kom., Pinus densiflora S. et Z., Taxus cuspidata S. et Z., Quercus xmccormickii Carruth et al.*	*Bam busoideae, Quercus myrsinaefolia Bl., Cinnamomum camphora Sieb., Buxus microphylla var. koreana NAKAI, Pinus densiflora S. et Z., Antipathes japonica Brook, Quercus acutissima CARRUTH, Zelkova serrata MAKINO et al.*	As a narrow zone whose temperature is more than 14˚C annually, it is largely located in the coast. Chejudo and other islands belong to this category
Freezing forest zone		*Picea jezoensis, Abies nephrolepis MAX., Larix olgensis var. koreana (Nakai) Nakai, Picea koraiensis Nakai, Pinus koraiensis S. et Z., Abies holophylla MAX., Pinus pumila REGEL et al.*		A zone that does not exist in flatlands and mostly is distributed in the plateau and highlands of Pyeongando and Hamgyeongdo, in which the annual temperature is less than 5˚C

Table 2. The Fuels for Experiments in this Study

Arbors		Collecting area
14 arbors in warm temperate forest zone	*Abies koreana, Acer palmatum, Acer pseudo–sieboldianum, Betula ermani var. communis, Carpinus laxiflora, Carpinus tschonoskii, Daphniphyllum macropodum, Pinus densiflora, Prunus maximowiczii, Prunus sargentii, Quercus mongolica, Quercus serrata, Styrax japonica, Taxus cuspidata*	Jeju–do

there was no change in weight in the unit of four hours while drying it at a temperature of 105˚C in a dryer, and for its result values, the mean values of measurement three times were used.

2.2 Initial Ignition Characteristics Analysis

Ignition characteristics analysis experiment was conducted to identify the initial combustion characteristics. Ignition is a behavior related to the start of combustion, and defines as points that represent that the heat occurrence speed is balanced with heat spread speed in the mechanism of speed control. For ignition characteristics, spontaneous ignition point that flameless ignition starts was measured and the flame duration was analyzed from both TTI (Time to ignition) that flame ignition starts after the flameless ignition and F.O. (Flame out).

For the measurement of spontaneous ignition point, an ignition temperature tester (KRS–RG–9000) from Kuramochi Group, Japan was used, and for the measurement of TTI (Time to ignition) and F.O. (Flame out), and a Dual Cone Calorimeter (ISO 5660–1, 2002) from Fire Testing Technology in England was used. Accordingly, more specific experimental condition is shown in Table 3.

For the measurement of spontaneous ignition point, the flame of flameless ignition was checked by the naked eye, and as the waiting period of ignition was 4s, the lowest temperature when materials are ignited spontaneously without source of ignition was measured (Hong Yun–Myeong *et al.*, 1992). In addition, for the measurement of TTI (Time to ignition), the time that ignition starts when materials were exposed to radiant heat was measured, and for the measurement of F.O. (Flame out), the time till the ignition finishes, i.e. the time when it is put out naturally was measured. The presence of flame was measured by the naked eye and recorded in an analysis system (ISO 5660–1, 2002).

2.3 Fire–Load Analysis

For the analysis of fire load, we used Dual Cone Calorimeter (ISO 5660–1, 2002) from Fire Testing Technology in England to determine THR (Total heat release) and Mean HRR (Mean heat release rate). For the measurement of total heat release (THR), heat release rate that is represented in a function to the time per superficial dimension of specimen was integrated and the values accumulated were obtained. The measurement of mean heat release rate (Mean HRR) is represented in the amount of heat volume that occurs per superficial dimension of specimen. Mean heat release rate is represented as the values that total heat release rate is divided by a given time, and for all the result values, the mean values of the results measured three times repeatedly were used.

RESULTS AND DISCUSSION

1. Moisture Content Characteristics

Table 4 shows the percentage of moisture content in the green leaves from 14 species of wood forest in the warm temperate forest zone, and each percentage of moisture content by each species of trees had different values within the range of 116~248%. As the degree of dryness of forest fuels is an important factor that may have an impact on the initial combustion on forest fire, the measurement results of the percentage of moisture content were classified into three things and the species of trees with low percentage of moisture content was analyzed. Eight species of trees (*Carpinus laxiflora, Abies koreana, Quercus serrata, Betula ermani var. communis, Pinus densiflora, Prunus maximowiczii,*

Table 3. The Experimental Conditions of the Ignition Temperature Measurement

Ignition temperature measurement		Dual cone calorimeter measurement	
Model	KRS–RG–9000	Sample holder size	100×100 mm
Method of measurement	group	Weight	50 g
Weight	20 mg	Heat flux	50 kW/m^2
Condition of material	living leaves	Test time	time until there was no more weight decrease
Waiting time of ignition	4 s	Condition of material	living leaves

Table 4. The Percentages of Moisture Contents for the Living Leaves of Arbor in Warm Temperate Forest Zone

Arbor species	Moisture contents (%)	Arbor species	Moisture contents (%)
Abies koreana	116.00	*Pinus densiflora*	142.00
Acer pseudo–sieboldianum	148.00	*Prunus maximowiczii*	149.00
Acer palmatum	224.00	*Prunus sargentii*	215.00
Betula ermani var. communis	139.00	*Quercus mongolica*	164.00
Carpinus laxiflora	132.00	*Quercus serrata*	121.00
Carpinus tschonoskii	140.00	*Styrax japonica*	221.00
Daphniphyllum macropodum	248.00	*Taxus cuspidata*	185.00

Carpinus tschonoskii, Acer pseudo–sieboldianum) contained 100~150% of moisture ratio, *Quercus mongolica* contained 151~200% of moisture ratio, and four species of trees (*Daphniphyllum macropodum, Prunus sargentii, Acer palmatum, Styrax japonica*) contained 201~250% of moisture ratio. Therefore, eight species of trees with relatively low percentage of moisture ratio are considered to have a relatively high risk of ignition, and in particular, as *Daphniphyllum macropodum* with the highest percentage of moisture content at 248% has a high percentage of moisture content 2.14 times more than the *Abies Koreana*. With the lowest percentage of moisture content at 116%, it is considered that its risk of ignition is relatively low.

Leaves contain moisture in three forms: water contains between cells; moisture contains in cells; moisture contains in crystal water. As dried fuels grow irregularly, the forms of cell changes irregularly, and so moisture content changes, which makes a difference in the percentage of moisture content (Lim Gyeong–Bin, 2007). The changes in water content is well known to be influenced by weather conditions such as temperature, wind, and humidity, and the degree of dryness of fuels is a factor that may have an impact on the ignition characteristics in the initial stage of combustion and the forms of wildfires on forest fire. Therefore, when the dried fuels are exposed to sunlight for a long time, they may be easy to ignite and spread to a wide area. On the contrary, as combustibles absorb moisture when the humidity is high and when it is damp and humid or in a shady place, much higher temperature is required for ignition (NFPA 921, 2011).

Vapour concentration of combustibles plays an important role in determining ignition quality and fire spread rate. As plants (combustibles) get dried, the ignition quality increases, which can make them more severely burnt. Plants with green leaves or plants with more moisture content are difficult to be ignited, and they absorb heat when moisture in plants evaporates, which makes them more slowly burnt. Once moisture disappears, temperature increases rapidly and reaches the ignition temperature of combustibles (NFPA 2011). Therefore, the ease of combustion is much related to the percentage of moisture content, and in particular, the important factor to such combustibles is a degree of dryness (NFPA 2011). Also, moisture acts as a catalyst for almost all reactions that are related to spontaneous ignition, and it also lowers the activation energy on the reaction and stimulates the reaction speed. Therefore, the presence of water makes the condition of spontaneous ignition better, but the quantitative relation is not clear (Kim Tae–Seok, 2009).

2. Ignition Characteristics

2.1 Self–Ignition Temperature Characteristics

Table 5 shows the spontaneous ignition point in the green leaves from 14 species of trees in the warm temperate forest zone. It was found that the spontaneous ignition point differed significantly at a temperature range of 251~383°C.

The spontaneous ignition point of the two trees of *Quercus serrata* and *Carpinus tschonoskii* was 251~300°C, which showed the lowest temperature range, 7 species of trees (*Pinus densiflora, Taxus cuspidata, Abies koreana, Quercus mongolica, Carpinus laxiflora, Acer palmatum, Acer pseudo–sieboldianum*) was 301~350°C, which showed the medium level, and finally 5 species of trees (*Prunus maximowiczii, Betula ermani var. communis, Daphniphyllum macropodum, Prunus sargentii, Styrax japonica*) was 350~400°C, which showed the highest spontaneous ignition point. Therefore, *Quercus serrata* and *Carpinus tschonoskii* were found to be relatively low in its spontaneous ignition point than other species of trees. In the ignition point of combustibles, plants with green leaves or plants with higher moisture content ratio are difficult to be ignited, i.e. they are slowly burnt as they absorb moisture as the moisture in the plants evaporate. Once moisture disappears, temperature continues to increase up and then reaches the ignition point of combustibles (NFPA 2011). Therefore, low spontaneous ignition point or low moisture content of combustibles plays an important role in determining the ignition quality and fire spread rate, *Quercus serrata* and *Carpinus tschonoskii* are higher in the ignition quality, which indicates that they may be severely burnt. As the flameless ignition point is low, it is considered that the flame ignition route spreads rapidly due to the moisture evaporation caused by the accumulation of heart as the flameless ignition proceeds for a long time.

Table 5. The Ignition Temperatures for the Living Leaves of Arbor in Warm Temperate Forest Zone

Arbor species	Ignition temperature (°C)	Arbor species	Ignition temperature (°C)
Abies koreana	324	*Pinus densiflora*	323
Acer pseudo–sieboldianum	322	*Prunus maximowiczii*	380
Acer palmatum	320	*Prunus sargentii*	381
Betula ermani var. communis	383	*Quercus mongolica*	332
Carpinus laxiflora	310	*Quercus serrata*	272
Carpinus tschonoskii	292	*Styrax japonica*	324
Daphniphyllum macropodum	380	*Taxus cuspidata*	324

Spontaneous ignition point is a phenomenon that ignition proceeds on the surface of combustibles slowly without any flame in the form of smoldering, and sometimes ignition occurs locally according to the circumstances. The factors that may affect the spontaneous ignition point include heat accumulation, thermal conductivity, heat generation, humidity, and superficial area. If there are any materials that may act as a catalyst in the reaction of heart generation, the reaction accelerates, which increases the heat accumulation. In other words, it is well known that it is easy to be ignited spontaneously, and a complex interaction of such particles makes the flameless ignition characteristics appear differently (Hyun Seong–Ho *et al.*, 2003).

In general, if the oxygen content of the air is less than 16%, combustion may reduce or stop, but most frequently, such natural macro–molecule substances as woods go through the smoldering process and again cause fire secondarily (Lee Seung–Hun, 2009). In addition, as flameless combustion is a phenomenon that the combustion continues passively when the temperature is low to reach the flame ignition or when there is a lack of oxygen, it largely produces white heat and smoke without flame and the chemical reaction continues slowly along the surface of combustibles from the deep part of fire, combustion spreads slowly from the inside of combustibles and may not be discovered for a long time, and it may proceed to the flame combustion if sufficient oxygen is supplied all of a sudden or if temperature rises up. In the process of imperfect combustion like smoldering, more than 10% of fuels become CO, which may be fatal to human body. So, if is known that it is a very dangerous fire (Lee Seung–Hun, 2009).

Therefore, the factors that may affect the ignition quality in fire detection through the classification of proper combustion characteristics of combustibles from an actual experiment of combustion characteristics can be considered, and from this, it can be considered that the fire spread rate or ordinary behavior can be determined.

2.2 Flame Ignition Time Characteristics

Table 6 shows the flame ignition time of green leaves from 14 species of trees in warm temperate forest zone. The flame ignition occurred only in *Carpinus tschonoskii*, but did not occur in other species of trees exclud-

Table 6. The Ignition Time for the Living Leaves of Arbor in Warm Temperate Forest Zone

Arbor species	Time to ignition (s)	Flame out (s)	Arbor species	Time to ignition (s)	Flame out (s)
Abies koreana	No ignition	–	*Pinus densiflora*	No ignition	–
Acer palmatum	No ignition	–	*Prunus maximowiczii*	No ignition	–
Acer pseudo–sieboldianum	No ignition	–	*Prunus sargentii*	No ignition	–
Betula ermani var. communis	No ignition	–	*Quercus mongolica*	No ignition	–
Carpinus laxiflora	No ignition	–	*Quercus serrata*	No ignition	–
Carpinus tschonoskii	61	79	*Styrax japonica*	No ignition	–
Daphniphyllum macropodum	No ignition	–	*Taxus cuspidata*	No ignition	–

Table 7. Heat Release Characteristics for the Living Leaves of Arbor in Warm Temperate Forest Zone

Arbor species	T.H.R (MJ/m^2)	Mean H.R.R (kW/m^2)	Flame duration time (s)
Abies koreana	27	20	No ignition
Acer palmatum	35	19	No ignition
Acer pseudo–sieboldianum	35	18	No ignition
Betula ermani var. communis	33	18	No ignition
Carpinus laxiflora	29	15	No ignition
Carpinus tschonoskii	38	20	18
Daphniphyllum macropodum	18	12	No ignition
Pinus densiflora	30	17	No ignition
Prunus maximowiczii	35	19	No ignition
Prunus sargentii	24	11	No ignition
Quercus mongolica	28	15	No ignition
Quercus serrata	30	16	No ignition
Styrax japonica	28	15	No ignition
Taxus cuspidata	33	20	No ignition

ing *Carpinus tschonoskii*. *Carpinus tschonoskii* was exposed to radiant heat and after 61s, its flame ignition was measured, and 79s after it was flame ignited, it was extinguished for 18s and the flame continued. The flame continuance time is shown in Table 7

In terms of such a difference in flame ignition, it is known that not only the percentage of moisture content but also the tissues of leaves and changes in components according to the changes of weather and the changes in subsequent volatile components affect the ignition phenomenon (Hyun Seong–Ho *et al*., 2003). In addition, flaming occurs in various temperatures according to the content of moisture, oil, and minerals, and the ease of flaming depends on the size and characteristics of combustibles, content of oil and minerals, weather conditions, and topography and direction. Therefore, that the ignition time is short means that combustion proceeds as rapidly as such and on fire occurrence, the combustion spread proceeds rapidly (Gang Seong–Dong *et al*., 2002), and it is also considered that the flame continuance time after flame ignition is the cause of increase in radiant heat and may have a direct impact on fire spread.

Like this, what some species of trees are weak or strong to wildfire depends on the difference in the ignition tome of tree leaves. According to the experimental results on the ordinary ignition temperature of green leaves, most trees die at a temperature of 150~180°C, carbonized at a temperature of 200°C, combusted at a temperature of 380°C, and flamed at a temperature of more than 400°C. At this time, the time that lasts till they are flaming is closely relate to the thickness of leaves and the moisture content within leaves (Gang Jeon–Yu *et al*., 2002). However, moisture acts as a catalyst in almost all reactions related to spontaneous combustion, thus reducing the activation energy of the reaction and stimulating the reaction speed, but the quantitative relations are not clear (Kim Tae–Seok, 2009).

The indicators of fire spread appear on the partially burnt combustibles and non–flammable materials. Such visual indicators include various damages of the remaining combustibles, carbonization pattern, discoloration, carbon stains, shapes, locations, and status. The analysis of the patterns appeared by various indicators in certain areas enables us to check the routes of fire spread in the region. To trace the fire process back, the use of systematic methods and tracing back the fire route can make us to reach the ignition point. This procedure is a standard method which is recognized by forest fire research (NFPA, 2011).

In forest fire, the fire spread is influenced by convective heat and radiant heat. In the low rise plants and leaf piles caused by convection heat, fire spreads to the higher branches and the top of the mountains. Then, as fire proceeds outward, radiant heat becomes a major vehicle of heat transfer. Radiant heat is a major method of heat transfer in combustibles which are located in lower places and mostly are shrubs and grasses on balanced surface. Therefore, for an analysis of fire behavior more exactly, the changes in the forest fire combustibles should be observed more carefully (NFPA, 2011).

Therefore, it is considered that ignition characteristics will be utilized as useful information for the estimation of the combustion routing in the detection of forest fire and the flame ignition of green leaves of *Carpinus tschonoskii* will be utilized as data for the identification of combustion type in the detection of crown fire.

3. Fire–Load Characteristics

Table 7 shows the heating characteristics of green leaves from 14 species of trees in warm temperate forest zone. Total heat release ranged in 18~38 MJ/m^2, and mean heat release ratio ranged in 11~20 kW/m^2.

The six species of trees (*Taxus cuspidata, Prunus maximowiczii, Betula ermani var. communis, Carpinus tschonoskii, Acer palmatum, Acer pseudo–sieboldianum*) released heat of 31~40 MJ/m^2 or so, 7 species of tress (*Pinus densiflora, Quercus serrata, Abies koreana, Quercus mongolica, Carpinus laxiflora, Prunus sargentii, Styrax japonica*) released heat of 21~30 MJ/m^2 or so, and *Daphniphyllum macropodum* released heat of 20 MJ/m^2 or less. Therefore, on the occurrence of wildfire, *Taxus cuspidata, Prunus maximowiczii, Betula ermani var. communis, Carpinus tschonoskii, Acer palmatum, Acer pseudo–sieboldianum* have relatively higher heating power, and thus if they proceed to crown fire, heat load becomes higher and fire strength becomes higher, and therefore it is considered that fire spread will proceed rapidly. In particular, as *Carpinus tschonoskii* proceeds with the flaming ignition, it appears that it has the highest heat load, and the reason why the heating power is so high seems to be attributable to the fact that there is a vivid combustion process while releasing a lot of heat when thermal cracking proceeds rapidly in the initial stage of combustion. In such process of flaming ignition, major components such as C, H, and S are all combined with oxygen, thus creating CO_2, H_2O, and SO_2 and the combustibles are completely extinguished, high amount of heating power increases the ambient temperature and so heat spread ratio proceeds rapidly, and such a rapid heat spread causes the fire spread so fast (Kim Hyun–Jung *et al*., 2004).

Heating power may have a large impact on the degree of damage as much as the duration that combustibles are combusted. The region of widespread damage indicates that there are important combustibles in the site, which is significant in determining whether fire load of combustibles may affect the fire spread from other locations (NFPA, 2011).

The degree of fire resistance of woods is a difference in composition of major components as well as moisture content ratio. It is known that needle leaf tree is susceptible to wildfire and oak trees are fire resist species. Its major components are cellulose, hemicellulose, and lignin, and it also contains a small amount of ashes, water and oil, oil refining, Tannin, pigment, etc. In terms of its percentage, it is known that cellulose is 50% both in needle leaf tree and broad leafed tree, hemicellulose 20% in needle leaf tree and 30% in broad leafed tree, lignin 30% in needle leaf tree and 20% in broad leafed tree, but its specific content difference is unrevealed. The chemical formula of cellulose is $C_6H_{10}O_5$. The molecular weight of cellulose, 162 g contains 72 g of carbon, 10 g of hydrogen, and 80 g of oxygen. To look it easily, almost half of the woods consists of cellulose, and to look at it from weight, half of this cellulose consist of oxygen. C and H are combustible materials in itself, and O that occurs on thermal cracking of cellulose helps to combust C and H although the oxygen concentration of the air lowers to 16% or less. As the oxygen is not sufficient, active combustion is not possible, but flameless chemical reaction (smoldering) continues. Smoldering is applicable to the combustibles using the natural high–molecular substances such as papers, etc and plant fiber such as cottons as well as woods (Lee Seung–Hun, 2009).

In the occurrence of heating power, absorption water evaporates at a heating with 100˚C or so, but if it is over 100˚C, structural absorption water releases and Pyrolysis initiates slowly, Pyrolysis rate is faster at 150˚C, hemicellolose degrades rapidly at 180~300˚C, cellulose degrades at 240~400˚C and lignin at 280~550˚C, the heating peak appears at 250˚C, 300˚C, and 400˚C, respectively. At this time, it is taken apart vigorously and causes exothermic reaction. Hydrogen is separated from the carbides with three major components at 500~1,000˚C and becomes into charcoal, and the leak of the creation of wood gas around 700˚C is caused largely by the creation of hydrogen (Shim Jong–Seop 1994). The exothermic reaction from such thermal cracking increase the ambient atmosphere and generates a large amount of smoke and at the same time fire grows rapidly, influenced by radiant heat. Therefore, the growth type of fire caused by flame, radiation, high temperature gas, and smoke creates the form of extinguishment from which researchers are able to know where the source of fire or part of fire is (Kim Tae–Seok 2009). Thus, flaming temperature and heating power are an investigation on the situation observed from the estimation of fire state and fire spread on fire investigation in order to provide some basis for understanding of the general matters at the time of fire.

The combustion routing represents the smoke and flame orientation that is involved in fire direction obviously. Fire flow is combusted in longitudinal and horizontal directions, influenced by various conditions. Therefore, various materials by route of fire flow, i.e., combustion route, remain extinguished in the form changed by the smoke and caloric heat. Each fire flow spread in the longitudinal and horizontal directions represents physical influence at the area that touches the route, and in particular, the directivity appears significantly at the part where combustion stops. Therefore, if we trace back the conclusion obtained from an exact investigation on the traces that physical phenomenon by fire flow leaves i.e., combustion route, we can reach the ignition part or ignition point ultimately. So it is considered that the combustion directions (Kim Tae–Seok, 2009) can be considered if the combustion characteristics are considered according to the species of trees to trace the combustion route.

CONCLUSION

This study could identify the initial ignition characteristics and fire load characteristics from the considerations of thermal characteristics in the green leaves from 14 species of trees in order to detect the crown fire in the warm temperate forest zone. So our findings are as follows.

1) The degree of moisture content in the green leaves from 14 species of trees from the warm temperate forest zone differed significantly in the range of 116~248%. In the green leaves of *Carpinus laxiflora, Abies koreana, Quercus serrata, Betula ermani var. communis, Pinus densiflora, Prunus maximowiczii, Carpinus tschonoskii, Acer pseudo–sieboldianum*, moisture content ratio is 100~150%, and they are classified into the species of trees with relatively lower moisture content ratio. In particular, the moisture content ratio of *Abies koreana* is 116%, which is the lowest moisture content ratio, which is 2.14 times lower than *Daphniphyllum macropodum* with the highest moisture content ratio and the risk of fire ignition was found to be higher.

2) Spontaneous ignition point differed significantly at a temperature range of 251~383˚C according to the species of trees. Both in *Quercus serrata* and *Carpinus tschonoskii*, the flameless ignition point is 251~300˚C, which means that the risk of flameless fire ignition is relatively high, and in particular, it was found that *Carpinustschonoskii* has the highest flame ignition risk.

3) Six species of trees such *Taxus cuspidata, Prunus maximowiczii, Betula ermani var. communis, Carpinus tschonoskii, Acer palmatum, Acer pseudo–sieboldianum* have a relatively higher heating power and classified into the species of trees with higher fire load, and so it is considered that the fire strength is relatively higher and fire spread proceeds rapidly if crown fire proceeds. In particular, Carpinus tschonoskii which showed flame ignition already was found to be the species of trees with the highest heating power.

4) In the detection of fire, ignition characteristics may be utilized as a useful data for the measurement of combustion routing, heating power may be able to affect the degree of damage in combustibles as much as they are combusted and also may provide an important clue to determine how fire spreads by fire load.

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