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CHARACTERIZATION OF IGNITION PROCESS OF THERMALLY TREATED WOOD BY CONE CALORIMETER

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ABSTRACT

This study examines the influence of thermal treatment on the ignition properties of Norway spruce (*Piceaabies* (L.) H. Karst.) and sessile oak (*Quercus petraea* (Matt.) Liebl.) wood. Using a cone calorimeter both untreated and thermally modified samples (180°C for 6 h) were analysed to determine key fire modelling parameters: combustion efficiency, critical heat flux, ignition temperature, thermal inertia, and thermal response parameter. Obtained results reveal that thermally treated wood exhibits higher combustion efficiency than its untreated equivalent, with spruce generally outperforming oak. The effect of thermal treatment on other properties was species-dependent. Thermally treated spruce showed an increase in critical heat flux and a decrease in both thermal inertia and the thermal response parameter. Conversely, thermally treated oak displayed a reduction in critical heat flux and an increase in both thermal inertia and the thermal response parameter. These results highlight the complex, species-specific effects of thermal modification on the fire behaviour of wood.

KEYWORDS:Critical heat flux, cone calorimeter,ignition temperature, thermal treatment, oak wood, spruce wood.

INTRODUCTION

Thermal modification of wood causes its controlled degradation, which results primarily in the decomposition of hemicelluloses. This kind of treatment increases the service life of wood materials without the use of toxic chemicals (Sandberg &Kutnar 2016). The content of cellulose, lignin, and extractives increases. The least stable component of the wood at high temperatures is hemicelluloses. In spruce wood, the thermal stability declines in the following order: mannose > xylose ~ galactose > arabinose. In oak wood, the least stable saccharides were galactose, arabinose, and mannose. Besides that, surface lightness decreases with increase of treatment temperature (Sikora et al. 2018).In the case of oak wood, it was found that different types of wood respond differently to thermal load. Earlywood is more sensitive to thermal degradation than latewood. This difference of thermal reactivity is attributedto the higher cellulose content of latewood. Earlywood, containing more lignin and hemicelluloses than latewood, is therefore more susceptible to thermal degradation (Hamada et al. 2016).

Thermal treatments lied to a reduction of hygroscopicity. A reduction of equilibrium moisture content improving the dimensional stability. Despite negligible rise of modulus of elasticity in less severe treatments (relatively low temperature and short time), this property is reduced by the increase of thermal treatments severity. Modulus of rupture also shows a decrease due to the severity of the thermal treatment applied (Costa et al. 2019).Thermally treated wood is less hygroscopic than untreated wood, andincrease in thermal treatment intensity reduces the equilibrium moisture content and improves the dimensional stability of wood mostly in tangential direction (Cai et al. 2019).Gurleyen et al. (2019) reported besides reduction of lightness also decreases of the adhesion strength, which is possibly due to the lower wettability and pH of the heat-treated wood surface(with the heat treatment decrease surface hardness too).The results of Xu et al. (2019) indicated that the dimensional stability is improved markedly due to the reduction of hydrophilic hydroxyl. The mechanical properties decreased after thermal treatment due to the thermal degradation of hemicellulose and cellulose (Xu et al. 2019).Thermal treatment is also able to improve of acoustic properties of wood and therefore is applied in production of musical instruments (Mania et al. 2020).The treatment process must be chosen according to the final use of the wood, since higher temperatures may limit the use of thermally treated wood, e.g. for construction purposes (Gaff et al. 2019).

Ignition is point indicating the start of burning. It is commonly known that ignition process depending on material properties and also on ambient conditions, e.g. temperature, chemical composition of atmosphere or ambient pressure (Molina & Shaddix 2007,Fereres et al. 2012, Martinka et al. 2012, Khalid 2013, Simoes et al. 2017, Mitu et al. 2019).Janssens (1991a) reported that the ignition can be divided into: piloted ignition (initiation of flaming combustion in the presence of a pilot) and spontaneous ignition (without a pilot). Piloted ignition (ISO 5660-1:2015) is considered the initiation of combustion during the cone calorimeter test. In this case, ignition occurs as follows (ISO 5660-1:2015):*(1)*Energy in the form of an external heat flux applied to thesurfaceis partially absorbed, partially used to raise the temperature of a thin surface layer, and partially transferred as heat to lower layers.*(2)*Gaseous substances (water and products of pyrolysis and thermo-oxidation) are released from thesurface of the sample.*(3)*The released gases mix with the air. *(4)*Once a sufficient concentration of flammable products from thermo-oxidation and pyrolysis is reached, flaming combustion is initiated.

For the description of initiation, equations are used that describe the dependence of the time to initiation not only on ambient conditions (especially temperature or heat flux) but also on the properties of the combustible material. In the case of wood, these properties can be significantly influenced by its thermal treatment. For this reason, this study deals with the research of the influence of the thermal treatment of wood on its initiation characteristics).

MATERIAL AND METHODS

Two wood species, Norway spruce (*Piceaabies* (L.) H. Karst.) and sessile oak (*Quercus petraea* (Matt.) Liebl.), were used to prepare the samples. Each sample measured (100×100) ± 1 mm, with a thickness of 20 ± 0.5 mm. The tangential surface of the samples was exposed to the external heat flux during testing. To ensure consistent moisture content, all samples were oven-dried at 103 ± 2°C until a constant mass was achieved.Following the initial drying, a subset of the samples underwent thermal modification. This treatment was conducted in ambient air at atmospheric pressure (100±2) kPa, with a temperature of 180°C, for duration of 6 h. Fire behaviour was then investigated using a cone calorimeter, with the test procedure strictly adhering to the ISO 5660-1:2015. The samples were tested at five different heat flux levels: (20, 25, 30, 35, and 40) $kW \cdot m^{-2}$. Further details regarding the samples and pre-test conditions can be found in the Tab. 1.

Tab. 1: Basic properties of investigated samples and pre-test conditions.

Wood	ρ ($kg \cdot m^{-3}$)	Treatment	ML (%)	Pre-test conditions			C-factor
				AT(°C)	BP(kPa)	RHA(%)	
Spruce	392.1±43.0	Raw	0	23 - 24	99.4 - 99.6	31 - 32	0.04234
		Thermally treated	1.85	21	99.8 - 99.9	29	0.04141
Oak	594.4±24.8	Raw	0	23 - 24	99.4 - 99.6	31 - 32	0.04234
		Thermally treated	2.14	21	99.4 - 99.9	29	0.04141

Values behind sign ± denote standard deviation, ρ: density, ML: mass loss during the thermal treatment, AT: ambient temperature, BP: barometric pressure, RHA: relative air humidity.

Combustion efficiency (CE), critical heat flux (CHF), ignition temperature (T_{ig}), convective heat transfer coefficient at ignition (h_{ig}), apparent thermal inertia (ATI), and thermal response parameter (TRP) values were calculated from the measured data. These are among the most important parameters for characterizing the initiation process of materials.

Combustion efficiency

CE is defined as the percentage of carbon released during combustion of biomass fuels in the chemical form of carbon dioxide (Ward & Hardy 1991). Ferek et al. (1998) mathematically express combustion efficiency by Eq. 1:

$$\mathrm{CE} = \frac{c(\mathrm{CO_2})}{c(\mathrm{CO_2})+c(\mathrm{CO})+c(\mathrm{HC})+c(\mathrm{PC})} \quad (1)$$

where:$c(CO_2)$ is the amount of carbon atoms released as CO_2, $c(CO)$ is the amount of carbon atoms released as CO, $c(HC)$ is the amount of carbon atoms released as unburned hydrocarbons, and $c(PC)$ is the amount of carbon atoms released as carbon particles (soot).

The sum of CO_2 and CO accounts for more than 95% of the carbon released during the combustion of biomass. CE is calculated from the measured concentrations of carbon-containing gases and particles above background released from the combustion of biomass fuels (Ward & Hardy 1991).Modified combustion efficiency(MCE) was reported in many studies, e.g. by Ferek et al. (1998), Zhang et al. 2008), Shen et al. (2011) and Calvo et al. (2015) in the form Eq. 2:

$$\mathrm{MCE} = \frac{c(\mathrm{CO_2})}{c(\mathrm{CO_2})+c(\mathrm{CO})} \tag{2}$$

Shen et al. (2013) found that neither the negative correlation between MCE and fuel moisture nor the positive correlation between MCE and volatile matter content was statistically significant. Ferek et al. (1998) stated Eq. 3 for calculation of CE from MCE:

$$\mathrm{CE} = \frac{\mathrm{MCE}-0.18}{0.82} \tag{3}$$

Critical heat flux and ignition temperature

The critical heat flux (CHF) can be defined as the lowest value of heat flux applied to a sample's surfaces that result in flaming ignition. Given the wide range of physical and chemical properties of samples, numerous calculation methods for CHF exist, which have been described by researchers such as Lawson & Simms (1952), Bluhme (1987), Rhodes &Quintiere (1996), and Tsai (2009).In this article, the CHF for the studied wood species was calculated using the method proposed by Janssens (1991a), which is suitable for wood-based materials.Janssens (1991a) and Tran & White (1992) derived Eq. 4 for CHF of a material with 500 kg.m^{-3} density, emissivity 1.0, and ignition temperature between 250°C to 550°C:

$$q = q_{cr}\left[1 + 0.73\left(\frac{k.\rho.c}{h_{\mathrm{ig}}^2.t_{\mathrm{ig}}}\right)^{0.547}\right] \tag{4}$$

where:q isincident heat flux (kW·m^{-2}), q_{cr} is CHF (kW·m^{-2}), k is thermal conductivity (W·m^{-1}·K^{-1}), $\rho$is density (kg·m^{-3}), $c$is specific heat (kJ·kg^{-1}·K^{-1}), h_{ig} is convection heat loss transfer coefficient at the ignition moment (W·m^{-2}·K^{-1}), and t_{ig} is time to ignition (s).

The surface temperature of the sample was measured using a Type K (NiCr-Ni) thermocouple, with record every second. This measurement required high precision and synchronization with the ignition time. As the temperature of the sample's surface increases rapidly at ignition, a significant rise can occur in a short time. To prevent inaccuracies, the ignition temperature was determined by fitting the measured data with a logarithmic function. The ignition temperature was then calculated directly from the equation of this curve (Fig. 1).

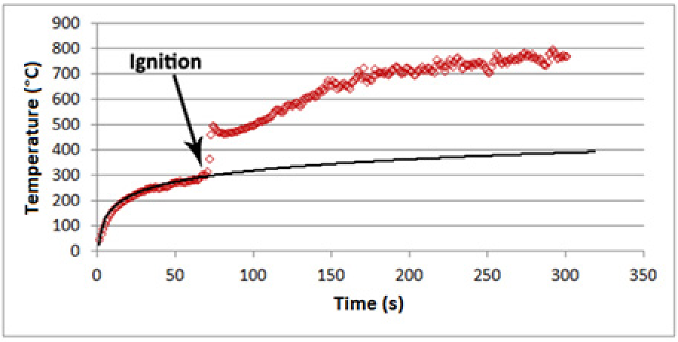

Fig. 1: Determination of ignition temperature from sample surface temperature.

Since charring of the wood's surface layer occurs before ignition, a simplification was made for further calculations: the sample was assumed to be a perfect black body (ε = 1.0). Ignition temperature (T_{ig} in K) can be then calculated from the Stefan-Boltzmann law (Eq. 5):

$$T_{ig} \cong \sqrt[4]{\frac{q_{cr}}{\sigma}} \tag{5}$$

where:σ is the Stefan-Boltzmann constant (5.67 × 10^{-8} W·m^{-2}·K^{-4}).

In addition to critical heat flux and ignition temperature; ignition is often characterized by the convection heat loss transfer coefficient at the ignition moment, apparent thermal inertia, and thermal response parameter.Convention heat loss transfer coefficient at ignition can be calculated by Eq. 6 derived e.g. by Janssens (1991a, 1991b, 2003), and Tran & White (1992):

$$h_{ig} = \frac{\varepsilon . q_{cr}}{T_{ig} - T_0} \tag{6}$$

where:ε is emissivity of surface (-) and T_0 is ambient temperature (K).

Apparent thermal inertia and thermal response parameter

Thermal inertia is a measure of material ability to resist a temperature variation (Dao et al. 2013).Since the thermal inertia is temperature dependent, the thermal inertia at ignition is not that obtainedat ambient conditions. Instead, the thermal inertia at ignition is an apparent value and it can be obtained from ignition data (Spearpoint &Quintiere 2001).Mathematically is expressed by Eq.7 as product of material density, specific heat capacity and thermal conductivity (Patel et al. 2011, Dao et al. 2013, Patel & Wang 2016):

$$P = k.\rho.c \tag{7}$$

where:P is thermal inertia (kJ^2·m^{-4}·K^{-2}·s^{-1}).

From Eq. 4 and Eq. 6 the theoretical apparent thermal inertia (ATI) can be calculated by Eq. 8. Equation similar to Eq. 8 is described e.g. by Dao et al. (2013):

$$P = \left(\frac{\frac{q}{q_{\text{cr}}}-1}{0.73}\right)^{\frac{1}{0.547}} . \left(\frac{\varepsilon . q_{\text{cr}}}{T_{\text{ig}}-T_0}\right)^2 . t_{ig} \tag{8}$$

The thermal inertia values calculated are mean apparent thermal effectivities between ambient and surface temperature at ignition (Dao et al. 2013).The thermal response parameter (TRP) allows obtaining an estimate of the material resistance to generate a combustible mixture. The higher the TRP value, the longer it takes for the material to heat up, ignite, and initiate a fire (Dao et al. 2013).Several authors provided the relationship for calculating the thermal response parameter (Tewarson 1994, Hagen et al. 2009, Xu et al. 2015) as Eq. 9:

$$\text{TRP} = \sqrt{k.\rho.c}.\left(T_{ig} - T_0\right) \tag{9}$$

where: TRP is thermal response parameter ($kJ \cdot m^{-2} \cdot s^{-1/2}$).

RESULTS AND DISCUSSION

Combustion efficiency (Tab. 2) was calculated in accordance with Eqs. 2 and 3 from data obtained in the first 300 s after sample ignition. The sampling interval was 5 s, therefore stated value of combustion efficiency are arithmetic mean (obtained from 60 data) for each sample. The CE for all investigated samples was in interval from 96.93 % to 99.40%.

Tab. 2: Combustion efficiency of spruce and oak wood samples at various external heat fluxes.

Sample	**Average combustion efficiency at given external heat flux (%)**				
	$20\ kW \cdot m^{-2}$	$25\ kW \cdot m^{-2}$	$30\ kW \cdot m^{-2}$	$35\ kW \cdot m^{-2}$	$40\ kW \cdot m^{-2}$
Raw spruce	97.21±1.82	98.16±0.89	99.16±0.29	99.22±0.23	99.13±0.14
Thermal treated spruce	98.67±0.53	98.59±0.29	99.30±0.08	99.19±0.15	99.40±0.11
Raw oak	96.93±2.17	97.08±1.47	97.35±1.72	98.45±1.14	98.61±0.77
Thermal treated oak	98.59±0.44	98.27±0.61	99.07±0.32	98.68±0.39	98.83±0.28

Values behind sign ± denote standard deviation.

Based on the relationships shown in Fig. 2, the critical heat fluxes for spruce and oak wood were determined. The CHF values ranged from 5.5 $kW \cdot m^{-2}$ to 10.0 $kW \cdot m^{-2}$ (Tab. 3), with coefficients of determination greater than 0.95.

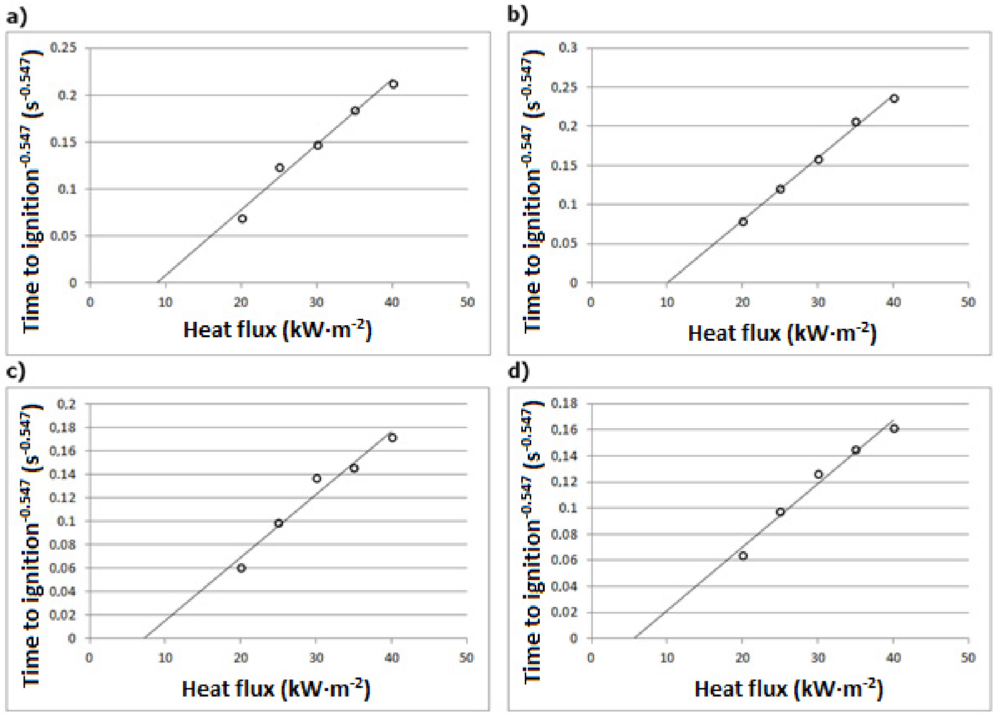

Fig. 2: Dependencies of time to ignition raised to the 0.547 power on heat flux for: a) raw spruce; b) thermally treated spruce; c) raw oak; and d) thermally treated oak wood.

Tab. 3: Critical heat flux and coefficient of determination of dependencies of time to ignition$^{0.547}$ on heat flux.

Sample	**Critical heat flux(kW·m^{-2})**	R^2**(-)**
Raw spruce	8.8	0.9824
Thermal treated spruce	10.0	0.9967
Raw oak	7.1	0.9592
Thermal treated oak	5.5	0.9772

The ignition temperatures, both the values measured directly and those calculated using Eq. 5, are presented in Tab. 4. The directly measured values range from 254 to 341°C, while the calculated values from Eq. 5 fall within the range of 286 to 375°C. For comparison Zachar et al. (2012) state flash-ignition temperature of wood in the range of 370 to 390°C. The difference cause is different methodology (measurement of air temperature flowing around the sample instead of surface temperature by cited authors).

Tab. 4 Ignition temperature of spruce and oak woods at heat fluxes in interval from 20 to 40 kW·m^{-2}.

Sample	**Measured ignition temperature at given heat flux (°C)**					**Average (°C)**
	20 kW·m^{-2}	25 kW·m^{-2}	30 kW·m^{-2}	35 kW·m^{-2}	40 kW·m^{-2}	
Raw spruce	302	337	309	341	313	320.4
Thermal treated spruce	304	334	328	296	314	315.2
Raw oak	295	287	308	328	319	307.4
Thermal treated oak	254	296	292	311	337	298
Calculated values of ignition temperature (°C)						
Raw spruce	354					
Thermal treated spruce	375					
Raw oak	322					
Thermal treated oak	286					

Tab. 5 shows the values for the convection heat loss transfer coefficient at ignition, apparent thermal inertia (ATI), and the thermal response parameter (TRP). These values were determined from Eqs. 6 through 8. Since ignition temperature is an input variable in these equations, each sample has two possible values for these parameters: one derived from the measured ignition temperature and another from the calculated ignition temperature.

Tab. 5: Average convention heat loss transfer coefficient at ignition moment, theoretical apparent thermal inertia and thermal response parameters for raw and thermally modified spruce and oak wood.

Sample	**Average convection coefficient at ignition ($W \cdot m^{-2} \cdot K^{-1}$)**		**Average theoretical apparent thermal inertia ($kJ^2 \cdot m^{-4} \cdot K^{-2} \cdot s^{-1}$)**		**Average thermal response parameter ($kJ \cdot m^{-2} \cdot s^{-1/2}$)**	
	According measured T_{ig}	According calculated T_{ig}	According measured T_{ig}	According calculated T_{ig}	According measured T_{ig}	According calculated T_{ig}
Raw spruce	29.7	26.6	0.2698	0.2134	136	152
Thermal treated spruce	34.1	28.3	0.2097	0.1439	112	134
Raw oak	25.1	23.8	0.4539	0.4080	181	190
Thermal treated oak	20.2	20.9	0.5575	0.5861	211	202

The combustion efficiency can be useful in indicating the relative abundance of flaming and smouldering combustion. Pure flaming has an MCE near 0.99 while the MCE of smouldering varies over a larger range (～0.65–0.85), but is most often near 0.8. Thus, an overall fire-integrated MCE near 0.9 suggests roughly equal amounts of biomass consumption by flaming and smouldering (Akagi et al. 2011). Reid at al. (2005) separated plumes by their MCEusing a 0.9 threshold to indicate flaming-dominated (>0.9) versus smouldering-dominated (<0.9) combustion, while acknowledging that the distinction is not sharp. Ward & Hardy (1991) assume that combustion efficiency ranges from 50-80% for smouldering combustion and from 80-95% for flaming combustion.Prapas et al. (2014) assume that incomplete combustion is generally the result of a combination of the following (Prapas et al. 2014):*(1)insufficient oxidizer*, such as in smouldering reactions;*(2)insufficient mixing of fuel and oxidizer*;*(3)excessive cooling of the reaction zone*, essentially freezing chemical reactions before carbon in the fuel has been fully converted to CO_2.

From the measured CO and CO_2 values, it is clear that during the first 5 min after the ignition of the tested samples, flaming combustion significantly predominated over smouldering. A very similar conclusion can be drawn from the results of Xu et al. (2015), who describe that only trace amounts of CO are released during wood combustion. Although the thermal treatment of wood removes substances that decompose at lower temperatures, the thermally treated samples still achieved slightly higher average combustion efficiency. In all cases (both thermally treated and untreated samples), the combustion efficiency was higher for spruce wood than for oak wood.Bruce et al. (1961) assume that the rate of spread of fire through a wood crib decreased in a curvilinear manner as the density of the wood increased. Harada (2001) states that the time to ignition of wood increased linearly with increasing sample density.According to Martinka et al. (2015) with the increasing density of spruce wood its resistance to ignition increases.Based on these findings, the lower combustion efficiency of oak wood can be attributed to its higher density.The influence of the higher resin content in spruce wood does not appear to be significant. Natural resins decompose in an inert atmosphere at temperatures between 120°C and 280°C (Tsanaktsidis et al. 2013). In air, decomposition can be expected to occur at slightly lower temperatures. Thermally treated wood should therefore have lower resin content, and its effect on combustion should be less pronounced. However, the combustion efficiencies are higher in thermally treated wood. This leads to the conclusion that resin content does not have a determining influence (and may even have a negative impact) on combustion efficiencies in this case.

In general, combustion efficiency increases with a rising heat flux. This trend is clearly visible in Fig. 3, which shows the average values for the tested samples. When the heat flux during measurement is higher, the sample surface is heated more intensely, which causes more complete combustion of the gases released. This is consistent with Xu et al. (2015), who notethat the effective heat of combustion increases slightly with increasing heat flux.Values for CHF, T_{ig}, h_{ig}, ATI, and TRP from other authors are summarized in Tab. 6. Authors who used higher external heat fluxes to determine CHF generally report higher values. Even higher heat fluxes are required for ignition without an initiator (Boonmee &Quintiere 2002). Conversely, very low critical heat fluxes (0.6 kW·m^{-2} to 1.5 kW·m^{-2}) were reported by Lawson & Simms (1952) when a pilot flame was used.Wang et al. (2010) describe a significant effect of atmospheric pressure on the critical heat flux value. According to Wang et al. (2010), a reduction in pressure of approximately 36% resulted in a nearly 90% increase in CHF. Most authors do not state this condition, which can complicate the comparison of results.

However, the calculated critical heat fluxes for both thermally treated and untreated spruce and oak were lower than those reported in most other studies. Since our measurements were conducted at a pressure of 99.4 kPa – 99.9 kPa, it's unlikely that other authors' measurements were taken at a significantly higher pressure. For example, the highest pressure ever recorded in London was just under 105 kPa, caused by an anticyclone (Burt 2020).

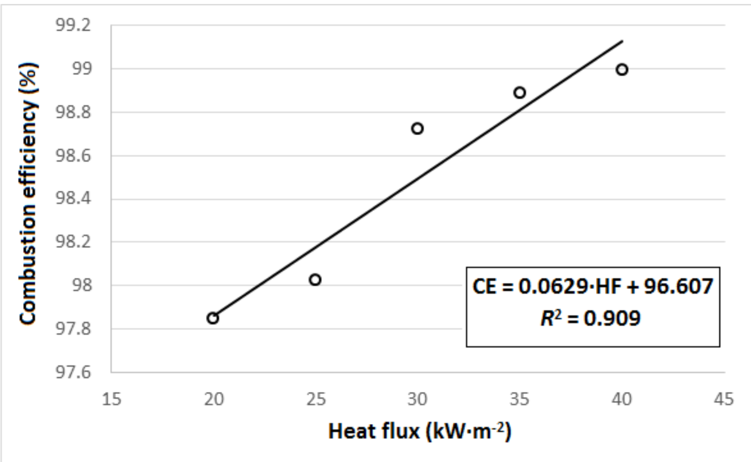

Fig. 3: Dependencies of combustion efficiency (CE) on heat flux (HF) for both thermally treated and untreated spruce and oak wood.

Mindykowski et al. (2019) determined the critical heat flux (CHF) for spruce wood to be 9.1 kW·m^{-2}, which is practically the same as the value measured in our samples. The authors also state that wood moisture had no effect on CHF. They considered spruce a thermally thick material and used external heat fluxes ranging from 12.5 kW·m^{-2} to 35 kW·m^{-2}. Based on these results, it seems that the differences in CHF values between thermally treated and untreated wood, as well as the values reported by other authors for horizontally positioned samples, are primarily due to the choice of ignition source and the range of external heat fluxes used. The influence of thermal modification on CHF is not obvious. A lower CHF is sufficient to ignite spruce wood compared to oak wood. As Spearpoint &Quintiere (2001) state, the magnitude of CHF depends on the sample's heat transfer coefficient. For various wood species, the heat transfer coefficient is strongly dependent on the material's density (Brischke et al. 2012). Therefore, the difference in CHF between spruce and oak wood is likely caused by their differing densities.While the critical heat flux (CHF) values are slightly lower than those reported by other authors, both the measured and calculated ignition temperatures fall within the range found in the literature. In three cases, the average of the measured values is lower than the value obtained by calculating from Eq. 4. One of the key assumptions of the method used to determine CHF is that ignition occurs when the surface reaches a given temperature (Janssens 1991b). Based on the measured and calculated ignition temperatures, it should therefore be possible to determine the material's emissivity at the moment of ignition. Under the given conditions, the emissivity (ε) would be in the range of 0.68 to 1.09, with an average value of 0.87. However, since ε must always be ≤ 1, it would be appropriate to determine it for individual samples from a larger number of measurements.

Tab. 6: Critical heat flux (CHF), ignition temperature (T_{ig}), convective heat coefficient at ignition (h_{ig}), thermal inertia (P) and thermal response parameter (TRP) of selected wood.

Sample	**CHF (kW·m^{-2})**	**T_{ig} (°C)**	**h_{ig} (W·m^{-2}·K^{-1})**	**P (kJ^2·m^{-4}·K^{-2}·s^{-1})**	**TRP (kJ·m^{-2}·s$^{-1/2}$)**	**Source**
Nordic spruce	19	488	NR	0.14	291	(Hagen et al. 2009)
Leadwood	15.0	422	NR	11.5	376.2	(Maake et al. 2020)
Mopani	14.4	350	NR	10.6	161.2	
Tamboti	5.9	460	NR	5.8	352.7	
Stinkwood	9.2	375	NR	5.9	173.6	
Yellowwod	1.3	460	NR	2.5	232.2	
Douglas fir	18	478	NR	NR	182	(Xu et al. 2015)
Scots pine	19	488	NR	NR	164	
Southern pine	19	488	NR	NR	201	
Shorea	16	456	NR	NR	152	
Merbau	40	643	NR	NR	275	
Plywood	11.6 4.7[a]	125.6 – 286.4[a]	NR	NR	205.7	(Tsai 2009)
Wood fiberboard	8.6 2.8[a]	108.8 – 185.7[a]	NR	NR	235.1	
Natural wood	12.2	339	NR	0.657	226	(Gan et al. 2019)
Densified wood	12.2	340	NR	1.21	308	
Redwood	11.7 13[a]	375	NR	0.22	NR	(Spearpoint &Quintiere 2001)
Douglas fir	12.2 12[a]	304	NR	0.25	NR	
Maple	10.6 12[a]	354	NR	0.67	NR	
Red oak	8.2	304	NR	1.01	NR	
Redwood	12.42	363	29.9	0.073[b] 0.045[c]	NR	(Tran & White 1992)

Southern pine	10.68	320	31.3	0.183^{b} 0.110^{c}	NR	
Red oak	10.53	315	31.4	0.360^{b} 0.178^{c}	NR	
Basswood	10.00	298	31.8	0.141^{b} 0.077^{c}	NR	
Western cedar	13.3	354	34.9	0.087	NR	(Janssens 1991b)
Redwood	14.0	364	35.9	0.141	NR	
Radiata pine	12.9	349	34.6	0.156	NR	
Douglas fir	13.0	350	34.6	0.158	NR	
Victorian ash	10.4	311	31.5	0.260	NR	
Blackbutt	9.7	300	30.6	0.393	NR	
Fir	11.6	302	24.4	0.25	136	(Batiotet al. 2014)

NR: not reported; ^{a} – experimental value; ^{b} – apparent value; ^{c} – ambient value.

The emissivity of wood is typically reported in the range of 0.75 to 0.94 for relatively low temperatures (20°C to 70°C) (Modest 2013). Evans & Emmons (1997) assumed an emissivity of 0.75 for wood combustion, which is representative of carbon surfaces at temperatures around 900°C. Xu et al. (2015) considered an emissivity of ε=1 when calculating the ignition parameters of wood. Spearpoint &Quintiere (2001) expected the emissivity to be around ε=0.72 before exposure, and this value to approach 1 as the surface chars due to the external heat flux. The average emissivity for the tested samples therefore falls within the range cited in the scientific literature.

The convection coefficient at ignition, theoretical apparent thermal inertia (ATI), and thermal response parameter (TRP) are all calculated using Eqs. 6 through 9. For these calculations, can be used either the ignition temperature measured by the thermocouple or the ignition temperature calculated from Eq. 5 based on the critical heat flux (CHF). The results from both methods are shown in Tab. 4. Due to the previously mentioned issue with the missing emissivity value, it seems more advantageous to use the values determined from the measured ignition temperature. The average convection coefficient at ignition for spruce wood is similar to what other authors have reported, while for oak wood it is lower (Tab. 6).The average theoretical apparent thermal inertia for both types of wood is in line with findings from other authors (Tab. 6). The value for spruce wood is lower than for oak, a fact that stems from the different densities of the wood species. As per its definition in Eq. 7, thermal inertia is directly dependent on density.The thermal response parameter (TRP) for both the raw spruce and oak wood corresponds to values published by other authors (Tab. 6). After thermal treatment, the TRP value for oak increases but remains within the typical range for wood found in the literature (Table 6). For thermally treated spruce, however, the value drops to 112 $kJ \cdot m^{-2} \cdot s^{-1/2}$, which is slightly lower than what is typical for wood-based materials (Tab. 6).

CONCLUSIONS

This paper investigated the impact of thermal treatment on the combustion efficiency and ignition parameters of Norway spruce and sessile oak wood, subjected to heat fluxes ranging from 20 to 40 $kW \cdot m^{-2}$. The key findings are summarized as follows:*(1)*Combustion efficiency: Thermally treated wood exhibited higher combustion efficiency than its untreated counterpart. Across all samples, spruce wood consistently showed higher combustion efficiency than oak wood.*(2)*Critical heat flux (CHF): Spruce wood demonstrated a higher critical heat flux than oak wood.*(3)*Ignition temperature: The effect of heat treatment on ignition temperature was dependent on both the wood species and the applied heat flux. On average, a slightly lower ignition temperature was observed for thermally treated wood.*(4)*Apparent thermal inertia (ATI) & Thermal response parameter (TRP): Spruce wood had lower ATI and TRP values than oak wood.Species-specific treatment effects:*(a)*Thermally treated spruce wood showed a decrease in both apparent thermal inertia and thermal response parameter compared to untreated spruce.*(b)*In contrast, thermally treated oak wood exhibited an increase in both apparent thermal inertia and thermal response parameter compared to untreated oak.

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