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Effect of Thermal Treatment on Combustion Process of Spruce Wood (*Picea abies*)

Učinak toplinske obrade na proces izgaranja drva smreke (*Picea abies*)

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ABSTRACT • This paper deals with the effect of thermal treatment of spruce wood on its burning process. Samples of 100 mm x 100 mm were dried out and then heat-treated at 150 °C, 200 °C, 250 °C and 300 °C. Thus prepared samples were tested on a cone calorimeter at a heat flow of 50 kW·m⁻². The obtained results clearly show that with the increasing temperature of the treatment, the released heat from the surface unit decreases and the unit weight increases. The carbon dioxide concentration in the flue gas increases as well, however, the optical density of the smoke decreases substantially. It can be stated that the burning of spruce wood is considerably affected mainly by the thermal treatment at temperatures above 200 °C. From the point of view of the use of spruce wood as fuel, the most optimal treatment temperature is 250 °C.

Key words: torrefaction, *Picea abies* wood, heat flux, heat release

SAŽETAK • U radu se razmatra učinak toplinske obrade smrekova drva na proces njegova gorenja. Uzorci dimenzija 100 x 100 mm osušeni su i zatim toplinski obrađeni na 150, 200, 250 i 300 °C. Tako pripremljeni uzorci ispitani su na konusnom kalorimetru, pri toplinskom toku od 50 kW·m⁻². Iz dobivenih se rezultata može uočiti da se s povećanjem temperature toplinske obrade smanjuje oslobođena toplina površinske jedinice i povećava jedinična težina uzoraka od smrekovine. Koncentracija ugljikova dioksida u dimnom plinu također se povećava, ali se optička gustoća dima znatno smanjuje. Može se također zaključiti da na izgaranje smrekovine uglavnom znatno utječe toplinska obrada pri temperaturama višim od 200 °C. S gledišta upotrebe smrekovine kao ogrjeva, optimalna je temperatura toplinske obrade tog drva 250 °C.

Ključne riječi: torefakcija, drvo smreke, toplinski tok, otpuštanje topline

1 INTRODUCTION

1. UVOD

The treatment of wood by thermal load can be divided into three basic areas on the basis of the required output raw material. Drying is intended to reduce wood moisture. It is usually performed at a temperature of up to 115 °C (Edvardsen and Sandland, 1999; Hansson and Antti, 2006; Zarea Hosseinabadi *et*

al., 2012; Sehlstedt-Persson, 1995). The second area is thermal modification.

Modern thermal modification processes are limited to temperatures no higher than 260 °C. As a result of thermally induced chemical changes to the macromolecular constituents, the physical and biological properties of wood are altered (Hill, 2007). Finally, wood is used for the preparation of torrefied wood. This semi refined material is an intermediate between

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wood and charcoal, which has undergone a mild pyrolysis in inert atmosphere, at temperatures from 200 °C to 300 °C and atmospheric pressure (Bourgois and Guyonnet, 1988).

Thermal decomposition of wood can be described using a five-reaction mechanism, consisting of three devolatilization reactions for the pseudo-components - hemicellulose, cellulose and lignin, and of two additional reactions in the air for char devolatilization and combustion (Broström *et al.*, 2012).

Heat-treatment affects the mechanical properties of wood, whereby hardwood species are more susceptible to this process than softwood. The decay resistance of heat-treatment may be achieved but at a high cost and with reduced mechanical properties (Kamdem *et al.*, 2002). Heat treatment mainly resulted in a darkening of wood tissues, improvement of the dimensional stability of wood and reduction of its mechanical properties (Bekhta and Niemz, 2003). Increased heat treatment and resulting weight loss reduce the modulus of rupture (MOR) and modulus of elasticity (MOE) (Mburu *et al.*, 2008). Živković *et al.* (2008) state that the results of laboratory tests show that the heat-treated wood, when compared to genuine wood, except of improvements in dimensional stability, also exhibits a lower equilibrium moisture content in room conditions. Results of Mburu *et al.* (2007) showed that resistance to fungi and termites was greatly improved by the treatment. The acidity and wood-water contact angle are higher and polar component of surface free energy is lower after thermal modification (Miklečić and Jirouš-Rajković, 2016).

A mild thermal treatment (modifying at 160 - 180 °C in oxygen-poor atmosphere) leads to clear changes of the measurable acoustic characteristics, such as Young's modulus, damping and sound velocity, so thermally modified wood is a material with favourable characteristics for making musical instruments (Pfriem, 2015).

As a solid energy carrier, biomass generally has a few disadvantages, which limits its use for coal replacement and as a feedstock for entrained flow gasification. The hydrophilic and fibrous nature, low calorific value and low bulk energy content imply high accumulated costs in the whole supply chain and severe challenges in more advanced conversion systems. By thermally pre-treating the biomass by torrefaction, these properties may be significantly improved (Strandberg *et al.*, 2015), so torrefaction is a promising technique for improving the biomass performance for energy utilization (Tapasvi *et al.*, 2012).

In contrast to fossil fuels, biomass has a unique potential for making positive environmental impact. In the plan of the sustainable biomass production and use, the carbon dioxide emitted would be absorbed by newly grown biomass. It can be burnt without emitting large amounts of nitrogen oxides, and with low emissions of sulphur dioxide (Quaak *et al.*, 1999).

During torrefaction, the main thermal decomposition reactions involve the hemicellulose polymers, resulting in improved fuel properties exhibited by the torrefied samples. Compared to raw samples, the com-

position of the torrefied samples is closer to that of coal, with higher carbon content and a lower volatile matter content, and with much higher hydrophobicity (Tapasvi *et al.*, 2012). The carbon contents of torrefied wood are greater than those of wood, but lower than those of charcoal. Carbon increases at the expense of oxygen and hydrogen, thus leading to decreases in both H/C and O/C ratios (Pentananunt *et al.*, 1990).

In comparison to non-thermally treated wood, torrefied biomass fuels contain a lower amount of volatile matter and a higher amount of fixed carbon (Ndibe *et al.*, 2015).

Both torrefaction temperature and reaction time have strong effects on the torrefaction process, but temperature effects are stronger than effects of reaction time (Tran *et al.*, 2013; Felffi *et al.*, 2005; Pimchuai *et al.*, 2010).

It was demonstrated that the weight loss of thermally modified wood is mostly the result of the reduction of the polysaccharide fraction, while hemicelluloses degraded faster than cellulose during heat exposure. The acid-insoluble lignin content increased with the severity of the treatment at the expense of the carbohydrate component. (González-Peña *et al.*, 2009) Similar results are described by Čabalová *et al.* (2013). Upon thermal decomposition of spruce wood with increasing temperature, the amount of lignin and the amount of extracts increased, but the abrasive layer had a decrease in extracts. At the same time, the polysaccharide fraction degraded significantly, the average polymerization degree of cellulose decreased where the crosslinking reactions occurred. The results of Calonego *et al.* (2016) show that the thermal modification of wood causes significant increases in the net calorific value, and the extractive content, and significant decreases in the holocellulose, galactose, xylose and glucose contents.

At higher temperatures, wood shrinks in the transversal plane, due to volatilization of wood constituents and due to a slight densification of the cell wall substance (González-Peña *et al.*, 2009).

The torrefaction process can also be applied to wood-based fuels. In terms of torrefied product properties, the torrefied samples absorb approximately one-third of the moisture compared to the raw fuels, and the total grinding energy decreases up to 40 - 88 % (Tapasvi *et al.*, 2012).

Degradation of hemicelluloses, cellulose and lignin and removing of moisture from the material, have a strong effect on the pelletizing properties of biomass. The friction in the press channel of a pellet mill increases, resulting in high pelletizing pressures that increase the energy uptake of the mill and might result in a decrease of capacity and in worst case in overheating of a blockage of the mill press channels (Stelte *et al.*, 2011). The common practice in pelletizing of thermally untreated biomass, using water to decrease energy consumption and to improve bonding properties, is not applicable in pelletizing of torrefied materials (Larsson *et al.*, 2013). The composition of torrefied briquettes at 220 °C does not undergo many changes.

However, at higher temperatures, changes in the composition are perceptible, with the briquette hemicellulose practically degraded and cellulose depolymerisation process initiated (Felfli *et al.*, 2005).

According to the report of the Ministry of Agriculture and Rural Development of the Slovak Republic and the National Forest Centre, in the year 2016, 9.3 mil. m³ of wood was produced, of which 55.2 % was wood of coniferous trees. During this period, the production of spruce was 61.6 % of coniferous trees. A large amount of spruce timber was significantly affected by the activation of harmful biotic agents (Moravčík *et al.*, 2017). Usually such a contaminated wood is not suitable for construction or furniture purposes and it can be used for energy purposes. Therefore, this paper deals with the possibilities of thermal treatment of spruce and its influence on the burning of the resulting material.

2 MATERIALS AND METHODS

2. MATERIJALI I METODE

For the measurements, 5 sample pieces of tangentially split spruce wood (*Picea abies* (L.) Karst.) with dimensions of 100 mm x 100 mm and 20 mm thickness were used. The samples were first dried to zero humidity at 102 °C for 48 hours. Subsequently, four of them were further thermally treated at 150 °C, 200 °C, 250 °C and 300 °C in a preheated furnace. The heat treatment was carried out for 4 hours in a muffle furnace under an inert atmosphere (nitrogen flow rate of 200 ml·min⁻¹). Finally, the samples were transferred to an exsiccator, where they cooled down to ambient temperature. The total time of procedure was approximately 55 hours (48 hours for drying, 4 hours of thermal treatment at appropriate temperature, approximately 3 hours for cooling). The percentage mass loss of samples due to their thermal treatment is shown in Figure 1. With the increase of treatment temperature, the weight loss of the sample also increases. Ramos-Carmona *et al.* (2017) attribute this phenomenon to hemicellulose and cellulose decomposition and to oxidation reactions. Barta-Rajnai *et al.* (2017) also describe strong decrease of the volatile extractive content. Since the spruce samples were thermally treated in a nitrogen atmosphere, the oxidation reactions did not occur and, therefore, it was possible to predict the effect of decomposition of the mentioned wood components.

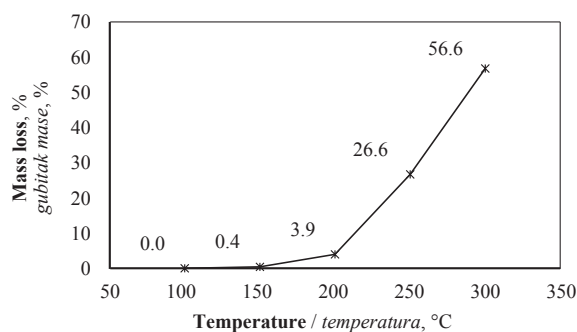


Figure 1 Dependence of the percentage mass loss on the temperature of thermal treatment

Slika 1. Ovisnost postotnoga gubitka mase o temperaturi toplinske obrade

The measurements were made on cone calorimeters meeting ISO standards 5660-1 (2015). Although a higher number of samples is required for the measurement of wood materials, due to the heterogeneous nature of wood, for cone calorimeter measurements the use of one sample for one heat flux is common, as evidenced by other authors. The samples were placed in the horizontal position under the emitter and initiation of the combustion was provided by an electric spark initiator. The measurement conditions are shown in Table 1. The time to ignition of the samples, the amount of heat released, the concentrations of carbon oxides in the flue gas and the amount of smoke released were observed.

3 RESULTS AND DISCUSSION

3. REZULTATI I RASPRAVA

The rate of heat release (Figure 2) is very similar for most samples. There is almost no oxidation of the sample material before initiation of flame burning. Volatile flammable substances are released, while the concentration of these substances in the mixture with air does not reach the value required for their ignition. This first phase takes a relatively short time, which can be attributed in particular to high external heat flow. As soon as the rate of release of the flammable fuel is sufficient, initiation occurs. Due to rapid homogeneous burning, the rate of heat release increases sharply. Once the sharp peak has been reached, a hardened layer begins to form on the surface of the samples. This acts as an insulator and partially restricts the heating of the

Table 1 Measurement conditions for individual samples

Tablica 1. Uvjeti mjerenja za pojedine uzorke

Treatment temperature, °C / Temperatura obrade, °C	100	150	200	250	300
Ambient temperature, °C / Temperatura okoline, °C	23	23	23	23	23
Barometric pressure, Pa / Barometarski tlak, Pa	101 054	101 030	100 977	100 771	100 768
Relative air humidity, % / Relativna vlažnost zraka, %	21	20	20	20	20
External heat flux, kW·m ⁻² / Vanjski toplinski tok, kW·m ⁻²	50				
Nominal duct flow rate, dm ³ ·s ⁻¹ / Nominalna brzina protoka, dm ³ ·s ⁻¹	24				
Sampling interval, s / Interval uzorkovanja, s	5				
Separation, mm / Odvajanje, mm	25				
C-factor / C-faktor	0.04296				

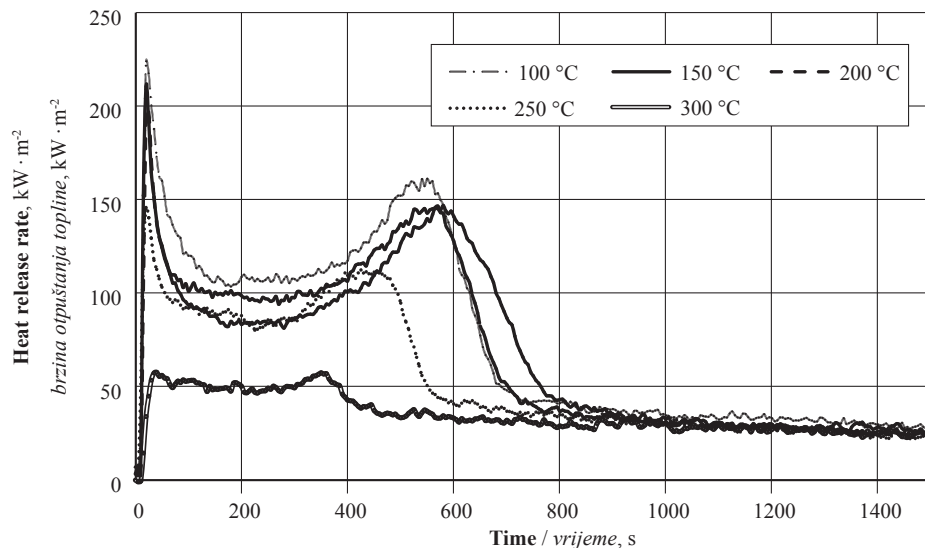


Figure 2 Time of heat release rate in combustion process of thermally-treated spruce wood
Slika 2. Vremenski tijek brzine otpuštanja topline u procesu izgaranja toplinski obrađene smrekovine

rest of the sample. At the same time, it partially prevents the penetration of volatile flammable substances into the burning area. Both of these mechanisms cause a decrease in the rate of heat release up to the phase of combustion stabilization. This area is visible in the graph in the form of a constant course. Then, it is followed by the second, considerably lower and wider peak. Hagen *et al.* (2009) state for the wood that the second peak occurs when the thermal wave reaches the back-insulating surface and the original material has already been pre-heated to the pyrolysis temperature, thereby effectively reducing the heat of the pyrolysis. After the flame burning, the rate of heat release decreases sharply. There are stages of smouldering and glowing, in which the heat is released mainly by the oxidation of carbon residues. The same course of burning in cone calorimetry testing has also been reported by Janssens (1991).

As the temperature of the thermal treatment increases, the value of both the first and the second peak decreases (Table 2). This decrease was also noted by Martinka *et al.* (2016) for spruce timber treated by different processes. Due to the high susceptibility of hemicelluloses to thermal degradation compared to

lignin described by various authors (Mburu *et al.*, 2008; Mburu *et al.*, 2007; Calonego *et al.*, 2016), this phenomenon can be attributed to the gradual thermal decomposition of hemicelluloses and cellulose in wood during the preparation of samples. In this way, the proportion of volatile flammable fuel, which is a fuel for homogeneous combustion, is declining. Burning of the specimen heated at 300 °C has a specific course, where both the first and the second peak do not reach any sharp maximum and only slightly differ from the steady burning phase.

In the samples treated thermally at temperatures of 250 °C and 300 °C, relatively faster rate of combustion starts to show up, which has also been stated by Pentananunt *et al.* (1990) for wood treated at similar temperatures (250 °C - 270 °C).

In terms of the initiation phase, an important parameter is the average rate of heat release in the first 60 seconds. For a spruce panel measured on a cone calorimeter, Östman *et al.* (1985) indicate a value of 172 kW·m⁻². The dried spruce was measured with a very similar result at a level just above 166 kW·m⁻² (Figure 3). It is clear from the other measurements that the first-minute average heat release rate decreases, with

Table 2 Results of thermally treated samples of spruce wood
Tablica 2. Rezultati toplinski obrađenih uzoraka smrekovine

Treatment temperature, °C / Temperatura obrade, °C	100	150	200	250	300
Time to ignition, s / Vrijeme do zapaljenja, s	9	8	8	8	12
First peak HRR*, kW·m ⁻² / Prvi vrh HRR*, kW·m ⁻²	223.76	210.17	196.49	145.44	57.25
Second peak HRR*, kW·m ⁻² / Drugi vrh HRR*, kW·m ⁻²	160.81	146.45	144.95	112.07	59.97
TSR**, m ² ·m ⁻²	343.17	225.35	194.07	103.46	3.65
Mean HRR*, kW·m ⁻² / Srednja vrijednost HRR*, kW·m ⁻²	65.90	60.09	60.09	48.40	32.64
Mean EHC***, MJ·kg ⁻¹ / Srednja vrijednost EHC***, MJ·kg ⁻¹	16.23	15.84	16.76	17.38	21.84
Mean MLR****, mg·s ⁻¹ / Srednja vrijednost MLR****, mg·s ⁻¹	35.89	33.52	31.70	23.62	12.53
Mean CO yield, mg·g ⁻¹ / Srednja vrijednost prinosa CO, mg·g ⁻¹	27.36	28.60	28.88	44.70	80.12
Mean CO ₂ yield, g·g ⁻¹ / Srednja vrijednost prinosa CO ₂ , g·g ⁻¹	1.35	1.34	1.43	1.52	1.81
THR*****, MJ·m ⁻²	118.57	108.07	108.07	87.15	58.67

*Heat Release Rate / brzina oslobađanja topline; **Total Smoke Release / ukupno ispuštanje dima; ***Effective Heat of Combustion / učinkovita topline izgaranja; ****Mass Loss Rate / brzina gubitka mase; *****Total heat release / ukupno oslobađanje topline

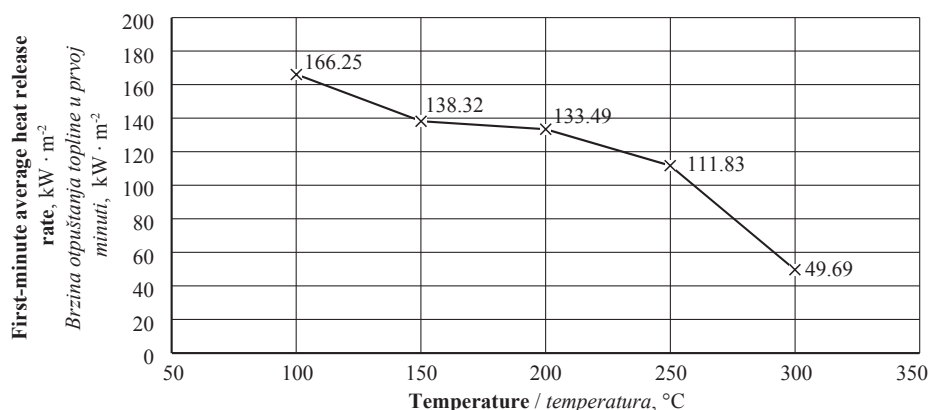


Figure 3 Influence of thermal treatment temperature on the first-minute average heat release rate in combustion of spruce wood

Slika 3. Utjecaj temperature toplinske obrade drva na brzinu otpuštanja topline u prvoj minuti izgaranja smrekovine

the temperature growth of the thermal spruce treatment, which is mainly due to the declining heat release rate. The decrease in the first peak of the heat release rate is also directly related to the decreasing maximum heat release energy (Table 2), which is an important indicator for the first phase of fire propagation.

The treatment temperature had a strong effect on total smoke release (Table 3). While dried wood released a smoke during the flame corresponding to an optical density of 345 m²·m⁻², the wood torrefied at 300 °C no longer showed any smoke. Similar results were described by different authors. Pentananunt *et al.* (1990) indicate that the torrefied wood showed significantly less smoking during combustion compared to untreated wood. Felfi *et al.* (2005) state that, from the combustion point of view, decreases in O/C and H/C ratios are favorable since less smoke and water vapour are formed, improving the performance of briquettes and contributing to energy loss reduction. The release of less smoke can be attributed to a gradual change in the soot formation mechanism in samples undergoing the process of thermal treatment (Mitchell *et al.*, 2016).

Results of individual measurements are shown in Table 2. The time for sample ignition does not show a large diffusion in the specimens modified to 250 °C. The value of 8 s to 9 s is comparable to that reported for spruce by Östman *et al.* (1985) Initiation of the sample modified at 300 °C occurred slightly later than in the previous samples. Due to the very low peak of heat release rate and the visual observation at which the flame did not differ from other samples, it is clear that the amount of volatile combustible in the sample was small. Initiation of volatile flammable mixtures with air was, therefore, delayed.

Mean heat release rate per unit area and hence a total heat release does decrease with the increasing temperature of the treatment. However, since the heat treatment changes the weight of the samples, the mean effective heat of combustion increases. This result is consistent with the calorific value of wood due to thermal treatment (Calonego *et al.* 2016). At the same time, the yield of carbon dioxide and carbon monoxide increases. This is probably due to the higher carbon content of thermally modified wood compared to the orig-

inal material described in the literature (Pentananunt *et al.*, 1990).

4 CONCLUSION 4. ZAKLJUČAK

The previous thermal treatment in an inert atmosphere has a notable influence on burning spruce wood. The influence occurs partly already before the sample initiation, which is higher compared to other specimens in the case of the sample modified at the temperature of 300 °C. The heat release rate reaches lower maximum values with the increasing adjustment temperature and its course is getting balanced. Intensity as well as flame burning time decrease as a result of decreasing flammable fuel content. However, in the case of thermal treatment, the weight of the sample also decreases, resulting in an increase in effective heat of combustion. The burning rate showed a sharp increase in samples treated at 250 °C or higher. In terms of flammability, the increase in the temperature of the heat treatment was confirmed by its decrease. In the case of torrefied wood, this is almost a hundredfold change, which can be considered very positive when used as a fuel. It can be concluded that the notable change in the burning of the treated wood is caused mainly by temperatures of thermal treatment above 200 °C. The highest amount of heat released per unit mass, substantially lower total smoke release, and the most uneven heat release during burning was observed in the sample thermally treated at the temperature of 300 °C. However, since the heat release rate in this sample reaches values very close to the external thermal flux applied to its surface, from the point of view of the use of spruce wood as a fuel, the preferred treatment temperature appears to be 250 °C.

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