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INVESTIGATION OF THE INFLUENCE OF SPRUCE AND OAK WOOD HEAT TREATMENT UPON HEAT RELEASE RATE AND PROPENSITY FOR FIRE PROPAGATION IN THE FLASHOVER PHASE

Jozef Martinka – Danica Kačíková – Peter Rantuch – Karol Balog

ABSTRACT

This paper deals with investigation of the way heat treatment of Norway spruce wood (*Picea abies* (L.) Karst.) and English oak wood (*Quercus robur*) influences the heat release rate and propensity for fire propagation in the flashover phase. The heat release rate was determined by a cone calorimeter at two different heat flux densities (35 and 50 $kW \cdot m^{-2}$) in accordance with ISO 5660-1:2002. The propensity for fire propagation in the flashover phase was determined in accordance with C/VM2:2013 from the cone calorimeter data measured at 50 $kW \cdot m^{-2}$. Three kinds of samples were used: heat untreated, heat treated in accordance with the ThermoWood – Thermo-S programme (maximum temperature during the heat treatment was 190 °C for spruce wood and 185 °C for oak wood) and heat treated in accordance with the ThermoWood – Thermo-D programme (maximum temperature during the heat treatment was 212 °C for spruce wood and 200 °C for oak wood). Obtained results proved that heat treatment of spruce and oak wood has no impact on the propensity for fire propagation in the flashover phase. The time interval to reach the flashover phase of both heat treated and untreated spruce and oak wood was from 120 to 600 seconds. The heat treatment of spruce wood by both used thermal programmes and heat treatment of oak wood using the ThermoWood – Thermo-D programme caused a significant decrease in the heat release rate. The heat treatment of oak wood using the ThermoWood – Thermo-S programme has no significant impact upon the heat release rate.

Key words: Flashover, Heat release rate, Heat treatment, Oak wood, Spruce wood.

INTRODUCTION

Heat treatment is one of the methods of protecting wood, which increases its resistance to biological degradation and the influence of weather, improves its aesthetic value, dimensional stability, thermal insulation and acoustic properties and simultaneously decreases its hygroscopicity. The main disadvantage of heat treatment is worsening of the majority of mechanical properties (mainly impact strength, firmness and hardness). On the other hand, some mechanical properties may improve following heat treatment (modulus of elasticity and also, in certain conditions, hardness) (REINPRECHT 2008, REINPRECHT and VIDHOLDOVÁ 2011).

A fairly large number of scientific works have investigated the influence of thermal load conditions of wood and wood-based materials upon changes to the chemical composition and selected physical properties, e.g.: REINPRECHT *et al.* (1999), SOLÁR *et al.* (2001), KAČÍKOVÁ *et al.* (2006), GONZÁLES-PEÑA *et al.* (2009), KAČÍKOVÁ and KAČÍK (2009), DZURENDA and JANDAČKA (2010), KUČEROVÁ *et al.* (2011), DZURENDA and DELIISKY (2012), HRONCOVÁ *et al.* (2013) and YUN *et al.* (2015). The results of the cited scientific works prove that the thermal load of wood and wood-based materials results in a decrease in the hemicellulose content and the average polymerisation degree of cellulose and, at the same time, the lignin content increases. The influence of heat treatment of wood upon its fire resistance properties was only assessed in scientific works by the THERMOWOOD ASSOCIATION (2003), WANG and COOPER (2007) and MARTINKA *et al.* (2013). The results of the cited scientific works prove that the heat treatment of wood affects the decrease in the maximum as well as the average rate of heat release and, at the same time, affects the increase in carbon monoxide yield. The results of the scientific works of WANG and COOPER (2007) further prove that the heat treatment of wood in plant oils decreases its resistance to the spread of flame.

However, the influence of heat treatment on the propensity of wood based materials for fire propagation in the flashover phase was not evaluated in any of the scientific works. A flashover is the non-linear form of the development of a fire from local to fully developed. A flashover phase is accompanied by a very rapid increase in temperature which is caused by the ignition of practically all flammable materials (ligno-cellulose based) in the section of fire within a short time interval. In terms of the development of fire, this is a key phase since after it is reached, conditions in the fire section are incompatible with life. Another reason for the decisive effect of this phase is the fact that until a flashover is created, fire extinguishing may save the fire section but after it is reached, action is primarily focused upon protecting adjacent fire sections.

The only standardised test for assessing the behaviour of material in the flashover phase is a test in accordance with ISO 9705:1993. Based on the results of this test, materials are classified into one of four categories: FO-1 (flashover does not occur during the test), FO-2 (flashover occurs within a time interval from 600 to 1200 s), FO-3 (flashover occurs within a time interval from 120 to 600 s) and FO-4 (flashover occurs within a time interval up to 120 s from the start of the test).

A disadvantage of the test in accordance with ISO 9705:1993 is that it is a demanding testing method in terms of finances and time. For the mentioned reasons, the scientific work by KOKKALA *et al.* (1993) describes a methodology for predicting the flashover category of a material based on the results of tests on a cone calorimeter using a testing method in accordance with ISO 5660-1:2002, loading the sample with a heat flux with a density of 50 $kW.m^{-2}$. The KOKKALA *et al.* (1993) method was implemented into several foreign technical standards and regulations. An example of such implementation is the technical standard C/VM2:2013 (New Zealand), where the flashover category of a material is specified for its use in escape routes in compliance with the cited method.

The aim of the submitted script is to evaluate the influence of heat treatment of Norway spruce (*Picea abies* (L.) Karst.) and English oak (*Quercus robur*) upon heat release rate and propensity for fire propagation in the flashover phase.

THE EXPERIMENTAL PART

Samples of Norway spruce (*Picea abies* (L.) Karst.) and English oak (*Quercus robur*) with dimensions of 100 × 100 × 20 mm were used in the research. Samples of both wood species were divided into three groups of ten pieces. The first group was formed of samples of wood which has not been heat treated. The second group was heat treated using the heat programme for the production of ThermoWood – Thermo-S and the third group of underwent the heat programme for the production of ThermoWood – Thermo-D.

The heat programme for the production of ThermoWood – Thermo-S from spruce wood: in the first phase, heating from 20 to 100 °C for 5 hours and then from 100 to 130 °C for 13 hours; in the second phase, heating from 130 to 190 °C for 5.5 hours maintained at a temperature of 190 °C for 3 hours; in the third phase, gradual cooling from 190 to 20 °C for 9.5 hours.

The heat programme for the production of ThermoWood – Thermo-S from oak wood: in the first phase, heating from 20 to 100 °C for 5 hours and then from 100 to 130 °C for 13 hours; in the second phase, heating from 130 to 185 °C for 5.5 hours maintained at a temperature of 185 °C for 3 hours; in the third phase, gradual cooling from 185 to 20 °C for 9.5 hours.

The heat programme for the production of ThermoWood – Thermo-D from spruce wood: in the first phase, heating from 20 to 100 °C for 5 hours and then from 100 to 130 °C for 13 hours; in the second phase, heating from 130 to 212 °C for 5.5 hours maintained at a temperature of 212 °C for 3 hours; in the third phase, gradual cooling from 212 to 20 °C for 9.5 hours.

The heat programme for the production of ThermoWood – Thermo-D from oak wood: in the first phase, heating from 20 to 100 °C for 5 hours and then from 100 to 130 °C for 13 hours; in the second phase, heating from 130 to 200 °C for 5.5 hours maintained at a temperature of 200 °C for 3 hours; in the third phase, gradual cooling from 200 to 20 °C for 9.5 hours.

Heat treatment was carried out in a muffle furnace in an air atmosphere at atmospheric pressure. Prior to the test, samples were dried using a cone calorimeter to zero absolute humidity at 103 ± 2 °C. The average densities of the investigated samples are shown in Table 1. The lower density of heat treated wood compared to untreated was caused by heat treatment.

Tab. 1 Average densities of investigated samples.

Sample	Density ($kg \cdot m^{-3}$)
Untreated spruce	423 ± 6
Thermo-S spruce	395 ± 8
Thermo-D spruce	346 ± 11
Untreated oak	719 ± 12
Thermo-S oak	692 ± 4
Thermo-D oak	664 ± 8

Samples were tested using a cone calorimeter and a testing method in accordance with ISO 5660-1:2002. Samples were investigated at two densities of heat flux from the cone radiator (35 and 50 $kW \cdot m^{-2}$). Each test (for one wood species, one method of heat treatment of a sample and heat flux density) was repeated five times. The average values are stated as resulting values.

The propensity for fire propagation in the flashover phase was evaluated using the method by KOKKALA *et al.* (1993) in compliance with C/VM2:2013. Input data for calculating the propensity of material for fire propagation in the flashover phase is obtained using a cone calorimeter and method in accordance with ISO 5660-1:2002 when loading a sample with a heat flux with a density of 50 $kW \cdot m^{-2}$.

The basis of the KOKKALA *et al.* (1993) method is the calculation of an ignition index in accordance with equation (1) and a rate of heat release index in accordance with equation (2).

$$I_{IG} = \frac{1}{t_i} \ (\text{min}^{-1}) \tag{1}$$

I_{IG}: ignition index (min^{-1})
t_i: ignition time - the time within which the heat release rate from the sample first reaches 50 kW·m^{-2} (min)

$$I_Q = \int_{t_i}^{t_{end}} \left[\frac{\text{HRR}(t)}{(t - t_i)^m} \right] dt \ (-) \tag{2}$$

I_Q: heat release rate index (-)
HRR(t): instantaneous heat release rate at time t (kW·m^{-2})
t: time (s)
m: an empiric constant (two values, 0.34 and 0.93, are used in the calculation) (-)

The time to reach the flashover stage is calculated from inequations (3 to 6). If inequation (3) applies the material is classified in category FO-4, if inequation (4) applies the material is classified in category FO-3, if inequation (5) applies the material is classified in category FO-2 and if inequation (6) applies the material is classified in category FO-1. If the heat release rate does not reach 50 kW.m^{-2} during the duration of the test, the material is classified in category FO-1 (C/VM2:2013).

$$I_{Q(m=0,34)} > 6800 - 540 \cdot I_{IG} \wedge I_{Q(m=0,93)} > 2475 - 165 \cdot I_{IG} \tag{3}$$

$$I_{Q(m=0,34)} > 6800 - 540 \cdot I_{IG} \wedge I_{Q(m=0,93)} \leq 2475 - 165 \cdot I_{IG} \tag{4}$$

$$I_{Q(m=0,34)} \leq 6800 - 540 \cdot I_{IG} \wedge I_{Q(m=0,93)} > 1650 - 165 \cdot I_{IG} \tag{5}$$

$$I_{Q(m=0,34)} \leq 6800 - 540 \cdot I_{IG} \wedge I_{Q(m=0,93)} \leq 1650 - 165 \cdot I_{IG} \tag{6}$$

RESULTS AND DISCUSSION

The heat release rates from spruce wood samples are illustrated on Fig. 1 and from oak wood samples on Fig. 2. The heat release rate from spruce and oak wood samples on Figs. 1 and 2 are typical for lignin-cellulose materials and are comparable with data on the heat release rates of wood and wood-based materials published by PARKER (2009) and TRAN (2009).

The first local maximum on Figs. 1 and 2 correspond with the ignition of the tested materials. The decrease in the heat release rate after the first local maximum (ignition) was caused by the creation of a solid carbonised layer on the surface of the sample during burning. The solid carbonised layer on the surface of the sample slowed overheating of the non-degraded surface due to thermal radiation from the cone radiator and back heat flux from the flame. The result was a decrease in the rate of thermal degradation, the release rate of gaseous degradation products and the heat release rate. The issue of the creation of a carbonised layer under fire conditions and its effect upon the burning process is described in more detail by KAČÍKOVÁ and MAKOVICKÁ-OSVALDOVÁ (2009).

The second local maximum on Figs. 1 and 2 represents simultaneous flame and flameless combustion (glowing) of a solid carbonised residue. The reason for the second local maximum is the accumulation of heat in the sample and its subsequent overheating to a high temperature and rapid thermal degradation. The stated conclusion is in compliance with the results of the scientific works by CARVEL *et al.* (2011).

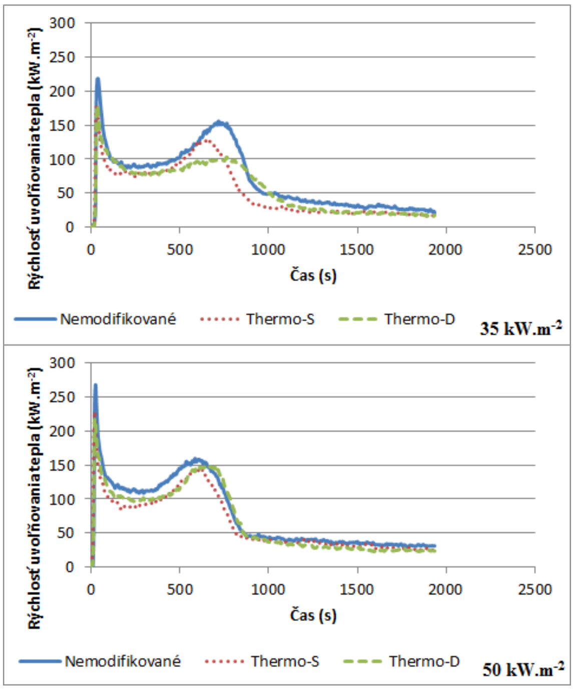

Fig. 1 Heat release rate from heat treated and untreated spruce wood loaded by heat flux density of 35 and 50 kW·m^{-2}.

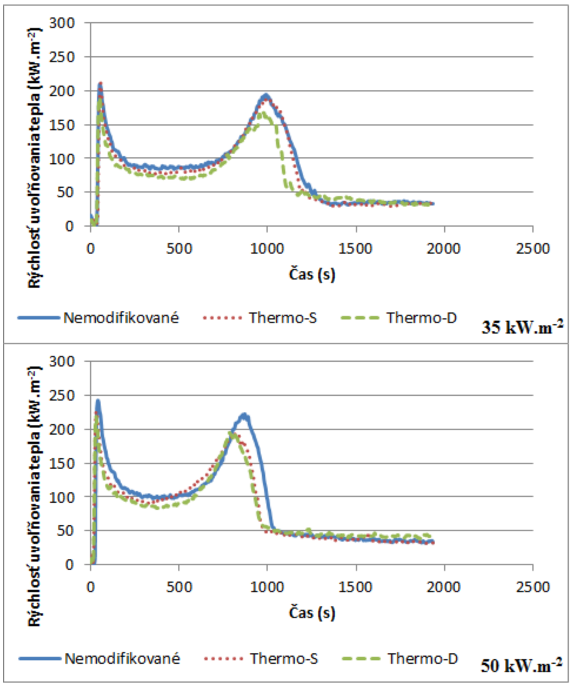

Fig. 2 Heat release rate from heat treated and untreated oak wood loaded by heat flux density of 35 and 50 kW·m^{-2}.

Visual analysis of Figs. 1 and 2 shows that heat treated spruce wood, when compared to untreated wood, has a lower heat release rate in the first and second local maximum. A similar conclusion also applies to oak wood, apart from oak wood heat treated using the

ThermoWood - Thermo-S heat programme with a heat flux of 35 kW·m^{-2} (under these conditions, it shows almost identical heat release rate values to wood untreated with heat).

The effect of heat treatment of spruce and oak wood upon the heat release rate was precisely evaluated based on the maximum and average heat release rated illustrated in Table 2, and based on Duncan's Test. The results of the Duncan's Test for spruce wood are shown in Tables 3 and 4, and for oak wood in Tables 5 and 6. A significant effect of heat treatment upon the heat release rate is indicated by a *p* value of the Duncan's Test lower than 0.05.

The data in tables 2 to 4 prove that the heat treatment of spruce wood has a statistically significant influence upon the decrease in the heat release rate when loaded with thermal radiation with a heat flux density of 35 as well as 50 kW·m^{-2}.

Tab. 2 Maximum and average heat release rates from heat treated and untreated spruce and oak wood.

Sample (-)	Heat flux (kW·m^{-2})	Maximum rate of heat release (kW·m^{-2})	Average rate of heat release (kW·m^{-2})
Untreated spruce	35	218	70
	50	268	76
Thermo-S spruce	35	178	53
	50	229	64
Thermo-D spruce	35	179	57
	50	218	67
Untreated oak	35	209	84
	50	243	88
Thermo-S oak	35	212	79
	50	226	82
Thermo-D oak	35	190	72
	50	218	80

Tab. 3 Duncan´s test p values used to assess the impact of heat treatment of spruce wood upon heat release rate (at 35 kW·m^{-2} heat flux density form cone heater).

Sample	*p* value of Duncan's test (-)		
	Untreated	Thermo-S	Thermo-D
Untreated	–	0.000011	0.000010
Thermo-S	0.000011	–	0.259935
Thermo-D	0.000010	0.259935	–

Tab. 4 Duncan´s test p values used to assess the impact of heat treatment of spruce wood upon heat release rate (at 50 kW·m^{-2} heat flux density form cone heater).

Sample	*p* value of Duncan's test (-)		
	Untreated	Thermo-S	Thermo-D
Untreated	–	0.000786	0.009532
Thermo-S	0.000786	–	0.385338
Thermo-D	0.009532	0.385338	–

Tab. 5 Duncan´s test p values used to assess the impact of heat treatment of oak wood upon heat release rate (at 35 kW·m^{-2} heat flux density form cone heater).

Sample	*p* value of Duncan's test (-)		
	Untreated	Thermo-S	Thermo-D
Untreated	–	0.148805	0.000530
Thermo-S	0.148805	–	0.033683
Thermo-D	0.000530	0.033683	–

Tab. 6 Duncan´s test p values used to assess the impact of heat treatment of oak wood upon heat release rate (at 50 kW·m^{-2} heat flux density form cone heater).

Sample	*p* value of Duncan's test (-)		
	Untreated	Thermo-S	Thermo-D
Untreated	–	0.071278	0.028580
Thermo-S	0.071278	–	0.622470
Thermo-D	0.028580	0.622470	–

The data in Tables 2 and 5 to 6 proves that oak wood heat treated using the ThermoWood - Thermo-D heat programme shows a lower heat release rate than oak wood untreated with heat. The data in the mentioned tables further proves that the difference in the heat release rate from oak wood untreated with heat and heat treated oak wood using the ThermoWood - ThermoS heat programme is not statistically significant,

The decrease in the heat release rate as a result of heat treatment was caused by a decrease in the content of hemicellulose and accompanying components, which subsequently caused a decrease in the amount of degradation volatile products released into the combustion zone. The stated conclusion is in compliance with the scientific works of REINPRECHT *et al.* (1999), SOLÁR *et al.* (2001), KAČÍKOVÁ *et al.* (2006), GONZÁLES-PEÑA *et al.* (2009), KAČÍKOVÁ and KAČÍK (2009), KUČEROVÁ *et al.* (2011), MARTINKA *et al.* (2013) and TODAR *et al.* (2015),

The measured and calculated values necessary for calculating the flashover category of the investigated samples using the method by KOKKALA *et al.* (1993) are shown in Table 7. The flashover category and time for reaching the flashover phase of the investigated samples is shown in Table 8.

Tab. 7 Measured and calculated values for calculating the propensity of spruce and oak wood for fire propagation in the flashover phase in accordance with KOKKALA *et al*. (1993) method.

Sample	t_i	I_{IG}	$I_{Q(m=0.34)}$ (-)	$I_{Q(m=0.93)}$ (-)	2475 - 165I_{IG} (-)	6800 - 540I_{IG} (-)	1650 - 165I_{IG} (-)
Untreated spruce,	20	3	20263	1311	1980	5180	1155
Thermo-S spruce	15	4	17051	1095	1815	4640	990
Thermo-D spruce	15	4	18144	1157	1815	4640	990
Untreated oak,	30	2	22755	1369	2145	5720	1320
Thermo-S oak	20	3	20940	1227	1980	5180	1155
Thermo-D oak	20	3	20125	1168	1980	5180	1155

Tab. 8 Time to the flashover phase of heat treated and untreated spruce and oak wood.

Sample	The time to reach the flashover stage	FO - category
Untreated spruce,	120 to 600	FO-3
Thermo-S spruce	120 to 600	FO-3
Thermo-D spruce	120 to 600	FO-3
Untreated oak,	120 to 600	FO-3
Thermo-S oak	120 to 600	FO-3
Thermo-D oak	120 to 600	FO-3

The time for reaching the flashover phase of a fire involving heat treated spruce and oak wood has not yet been stated in other scientific works, but the data in Table 8 for wood not treated with heat is in compliance with the results of the scientific works of OSTMANOVÁ and TSANTARIDIS (1994) and HANSEN and HOVDE (2002).

The data in Table 8 proves that the heat treatment of spruce and oak wood does not affect the for fire propagation in the flashover phase.

The data obtained about the effect of heat treatment of spruce and oak wood upon the heat release rate and the propensity for fire propagation in the flashover phase will mainly find application in evaluating the fire risk of technology with the presence of heat treated wood, as well as in addressing the fire safety of buildings (whose fire load is formed of the investigated materials), based on the fire engineering principles described in detail by, for example OSVALD and MÓZER (2012). A detailed description of the fire properties of spruce and oak wood are stated by, for example, ZACHAR (2010) and ZACHAR *et al.* (2012).

CONCLUSION

The submitted work investigated the influence of spruce and oak wood heat treatment upon heat release rate and propensity for fire propagation in the flashover phase. The obtained data proved that:

- the heat treatment of spruce wood using the heat programme for the production of ThermoWood Thermo-S and Thermo-D has a statistically significant influence upon the decrease in the heat release rate,
- the heat treatment of oak wood using the heat programme for the production of ThermoWood Thermo-S and Thermo-D does not have a statistically significant influence upon the decrease in the heat release rate,
- the heat treatment of oak wood using the heat programme for the production of ThermoWood Thermo-D has a statistically significant influence upon the decrease in the heat release rate,
- the heat treatment of spruce and oak wood using heat programmes for the production of ThermoWood Thermo-S and Thermo-D does not have any affect upon fire propagation in the flashover phase,

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Addresses of the authors

Ing. Jozef Martinka, PhD.
Ing. Peter Rantuch, PhD.
Prof. Ing. Karol Balog, PhD.
Slovak Technical University in Bratislava
Faculty of Materials Science and Technology in Trnava
Institute of Safety, Environment and Quality
Paulínska 16
917 24 Trnava
Slovak Republic
jozef.martinka@stuba.sk
peter:rantuch@stuba.sk
karol.balog@stuba.sk

Prof. RNDr. Danica Kačíková, PhD.
Technical University in Zvolen
Faculty of Wood Sciences and Technology
Department of Fire Protection
T.G. Masaryka 24
960 53 Zvolen
Slovak Republic
kacikova@tuzvo.sk