ACTA FACULTATIS XYLOLOGIAE ZVOLEN, 58(2): 121−131, 2016
Zvolen, Technická univerzita vo Zvolene
DOI: 10.17423/afx.2016.58.2.13

INFLUENCE OF PHYSICAL AND CHEMICAL CHARACTERISTICS OF SELECTED TREE SPECIES ON MASS LOSS AND RATE OF BURNING AFTER EXPOSURE TO RADIANT HEATING

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ABSTRACT

The main aim of this paper is to determine the mass loss of spruce, larch and beech wood during the process of thermal degradation and evaluation of the impact of selected primary factors (density, chemical composition) for mass loss, relative rate of burning and char layer. For evaluation of mass loss, we conducted a chemical analysis of wood samples by standard laboratory methods, which we exposed in the experimental device to radiant heat in distance of 50 mm, 40 mm and 30 mm. The achieved results confirmed the assumption that the mass loss depends primarily on the chemical composition of wood and the density. The results confirmed that larch has the lowest mass loss in distance 30 mm and 40 mm from source of radiant heat. The highest mass loss was recorded in beech wood in the same distance. Beech wood has the lowest resistance for distance 30 mm and 40 mm under thermal load of tested wood. The highest contribution of the material to spread fire showed at 30 mm distance larch, beech was lowest. Determined values were evaluated by software STATISTICA.

Key words: wood, burning, radiant heating, mass loss, thermal degradation, spruce, beech, larch.

INTRODUCTION

Wood is a natural organic material whose production, processing and utilization continues play an important role. Solve the problem of thermal degradation of wood mean complexly deal with of forthcoming changes in the wood characteristics due to the hight temperatures in the process of combustion (ZACHAR 2009).

Flammability of wood and other combustible material is to determine the conditions and factors that affect the combustion cycle. These can be devided into two groups – primary factors and secondary factors (HORSKÝ, OSVALD 1983, DZURENDA, JOŠČÁK 2000). The primary factors related to the chemical composition of wood and the physical and mechanical properties. Among the secondary properties include energy source factor, the factor of atmospheric impact and factor structure of the material.

The chemical composition of wood is varied by species, origin, sampling, age and state of health (KAČÍK, SOLÁR 1999). The wood of different wood species contains approximately 49.5 % of carbon, 6.3 % of hydrogen and 44.2 % of oxygen. The amount of nitrogen is in the range of 0.2–1.5 % depending on wood species. The proportion of ash in wood varies predominantly in the range of 0.2–1.2% (POŽGAJ *et al.* 1997, DZURENDA, PŇAKOVIČ 2016).

Extractives are typically lipids, phenolic compounds, terpenoides, fatty acids, resin acids, sterol and sterol esters, and waxes (DORADO *et al*. 2000; FERNANDEZ *et al*. 2001; KALLIOINEN *et al*. 2003; ISHIDA *et al*. 2007). The amount of extractives is always low, typically in the range of 2–5% (ZHANG *et al*. 2007), many of which are toxic, some are allergens or have detergent properties and other tree species provide a specific color or flavor (KAČÍK, SOLÁR 1999).

Wood density is an important property affecting all physical and mechanical characteristics of wood and the combustion process. Material with higher density uses more energy to ignite and burn, however the tree species with higher hemicellulose content are more flammable even in case, that they have higher density. Wood burning further depends on the surface treatment, sizes and moisture. Carpenter worked and planed boards are compared with unworked boards harder to ignite and burn worse - smooth surface reflects radiant energy source and an absorbing capacity of heat is changed. Burning rate decreases with increasing moisture content. In terms of the quality of the surface it is also important color. Thermal degradation changes the natural wood color to black - char layer, which is good absorbent of thermal radiation. Color change is caused by decrease of polysaccharide parts. It is associated with her autoretardant character (OSVALD 1997).

Wood burning presents a thermal decomposition of chemical bonds of basic components and change their chemical composition to formation many products (OSVALD 1997). The main components of wood are cellulose, hemicellulose, lignin and extractives (FENGEL, WEGENER 1984). Least resistant to thermal decomposition are hemiculloses, which decompose in temperature range 170–240 °C. Cellulose is more resistant to the action of heat. Decomposition of cellulose is moderate to temperature 250 °C ~~moderate~~, intense thermal decomposition occurs in the temperature interval 250–300 °C. The most durable component of wood is lignin. Its active decomposition takes place at temperatures of 300–400 °C (DRYSDALE 1999; JANSSENS 2004; KUČEROVÁ *et al*. 2011; KAČÍKOVÁ *et al*. 2011).

The most significant changes, that occur by exposure of wood to radiant heat include mass loss, anatomic changes, changes in the moisture content and dimensional stability, durability, mechanical and physical properties (KAČÍK, KAČÍKOVÁ 2010). Mass loss is one of the most important characteristics and is commonly used for expressing quality. According to several authors (OSVALD 1997; BLASI *et al*. 2001; WHITE 2001; MAKOVICKÁ-OSVALDOVÁ *et al*. 2014; ZACHAR, MARKOVÁ 2009), the mass loss depends on thermal action by the kind of tree species, environment, temperature and time of heating.

The aim of this paper is determine mass loss of spruce, larch and beech wood by the exposure of radiant heat in different distances and evaluation of the impact of selected primary factors (density, chemical composition) for mass loss, the rate of heating and char layer.

METHODOLOGY

Material

In the experiment was used spruce (*Picea abies* L. Karst) with average density $\rho \approx 486$ kg·m^{-3}, larch (*Larix decidua* Mill.) with an average density $\rho \approx 643$ kg·m^{-3} and beech (*Fagus sylvatica* L.) with density $\rho \approx 842$ kg·m^{-3}. The average moisture content of all tree species was $w = 9 \pm 0.5$ %. From these tree species have been tested samples sawn in radial-tangential direction of the wood trunk. For the purposes of the experiment, samples were adjusted to the dimensions of 20 × 20 × 150 mm. We used 5 pieces of samples for each measurement. Wood defects were not found control was performed visually.

Chemical analysis

Chemical analysis of selected kinds of wood was done under laboratory conditions by standard procedures. The samples were disintegrated to sawdust, which were divided by sieving on fractions 0–0.355 mm; 0.355–0.5 mm and 0.5–1.0 mm; were extracted 8 hours in a Soxhlet apparatus with a mixture of toluene-ethanol (2:1 v/v). Cellulose was determined by Seifert, holocellulose by Weiss, lignin using TAPPI Method (KAČÍK, SOLÁR 1999). Hemicellulose was calculated like difference holocellulose and cellulose. The resulting values are shown in Tab. 1.

Radiant heat

Experimental equipment is illustrated in Fig. 1.

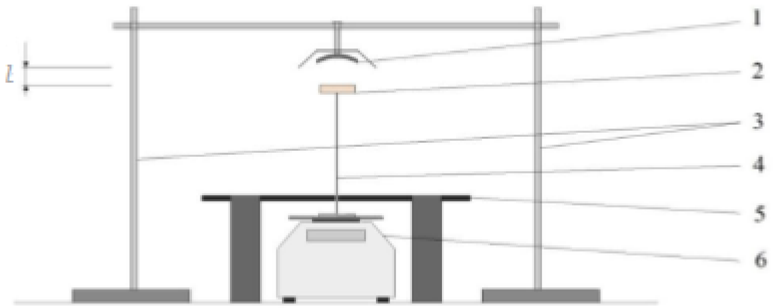


Fig. 1 - Scheme of experimental equipment: 1 – thermal infrared emitter, 2 – sample, 3 – load - bearing metal frame, 4 – metal stand, 5 - protection of the instrument, 6 - electronic scale, l - length of the test sample from the radiation source.

Experiment was carried out with the thermal infrared emitter T – 5 Elektro Prag with a power of 1000 W. The temperature on its surface reached a value of 750 ° C. Mass loss was recorded with electronic scales Sartorius Basicplus type BDBC 200 from Sartorius AG.
Before the experiment, the emiter was left warming 10 minutes. The sawed samples were placed in a desired distance – 50 mm from the surface of the emitter, where the average air temperature was 133 °C, 40 mm with an average temperature of 144 ° C and 30 mm from the emitter, with an average temperature of 163.5 ° C. Exposure time of all surface of samples to radiant heat lasted 10 min, during which of each 10 seconds was recorded mass loss from electronic scale.

CALCULATIONS

The relative mass loss was defined according to equation (1):

$$\boldsymbol{\delta_m\,(\tau)} = \frac{\Delta m}{m_{(\tau)}} \cdot \mathbf{100} = \frac{m_{(\tau)} - m_{(\tau+\Delta\tau)}}{m_{(\tau)}} \cdot \mathbf{100} \ (\%) \tag{1}$$

where: $\delta_m\,(\tau)$ relative mass loss in time (%)
$m_{(\tau)}$ mass of the sample in time (τ) (g)
$m_{(\tau+\Delta\tau)}$ mass of the sample in time ($\tau + \Delta\tau$) (g)
τ time (s) (KAČÍKOVÁ *et al*. 2008)

The relative rate of burning was defined according to equation (2):

$$\boldsymbol{\nu_r} = \left|\frac{\partial \delta_m}{\partial \tau}\right| \quad (\%\cdot s^{-1}) \tag{2}$$

where: ν_r relative rate of burning ($\% \cdot s^{-1}$)

$\partial\delta_m$ relative mass loss in time (τ) (%)
$\partial\tau$ time interval of subtracting of mass loss (s) (KAČÍKOVÁ *et al*. 2008)

The thickness of the char layer we determined as the ratio of the original thickness of the sample to Intact thickness of the sample material after thermal load according to equation (3):

$$\Delta h = 100 - \left(\frac{h1-h2}{h1} \cdot 100\right) \text{ (\%)} \tag{3}$$

where: Δh thickness of the char layer after the heat exposure (%)
h_1 thickness of the sample before the heat exposure (mm)
h_2 thickness of the sample after the heat exposure (mm) (KAČÍKOVÁ *et al*. 2007).

Statistical evaluation of the results was processed in the STATISTICA software as a basic two-factor analysis ANOVA.

RESULTS AND DISCUSSION

The content of extractives, lignin, hemicellulose and cellulose of samples of larch, spruce and beech wood are shown in tab. 1 as an average of three repeated determinations. Set values are in good agreement with literature data (PETTERSEN 1984; ČABALOVÁ *et al*. 2013).

Tab. 1 Chemical analysis of wood.

Wood	Extractives (%)	Lignin (%)	Hemicellulose (%)	Cellulose (%)
Spruce	1.39	27.22	32.78	46.39
Larch	3.32	26.40	31.95	42.12
Beech	1.64	22.57	47.37	39.10

The results of the experiments are presented graphically (fig. 2–4). By the action of the radiation source to the sample from distance 50 mm was the mass losses and the tendency of mass loss with time from 90 seconds, almost the same for all kinds of wood samples (see fig. 2). Beech wood showed the lowest average relative mass loss δ_m = 9.7 %. A similar course has a curve from 160. second of mass loss of larch wood when there was an increase of mass loss and the average relative mass loss reached δ_m = 10.5 %. The greatest mass loss occurred in spruce wood, which we observed from around the 90 seconds. The radiant heat acted to sample significantly with an average relative mass loss δ_m = 14.8 %.

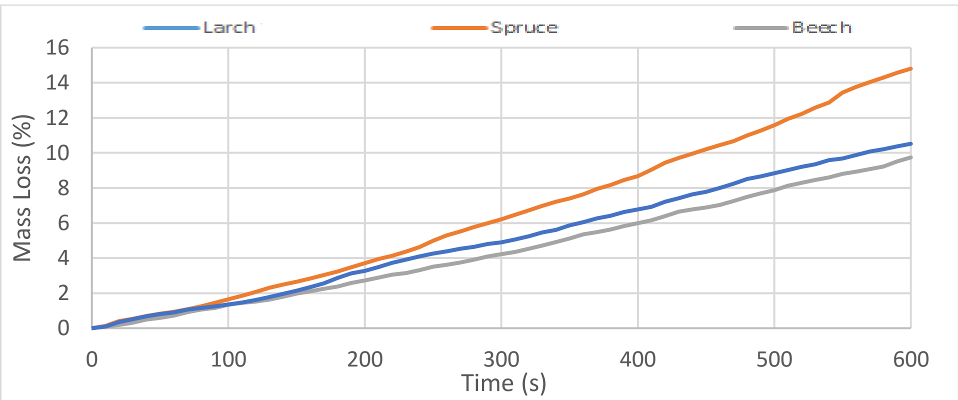


Fig. 2 The course of mass loss with time for distance of 50 mm.

At the distance of emitter 40 mm of samples were mass loss of beech and larch wood to 180 seconds relatively identical (fig. 3). Larch wood recorded the lowest average relative mass loss $\delta_m = 17.5$ %. Mass loss of beech wood from time of 300 seconds sharply increased and reached the average relative value $\delta_m = 47.5$ %. It is the highest average mass loss at distance of 40 mm. Mass loss of spruce wood has increasing tendency, especially after 50 seconds, with $\delta_m = 43.1$ %.

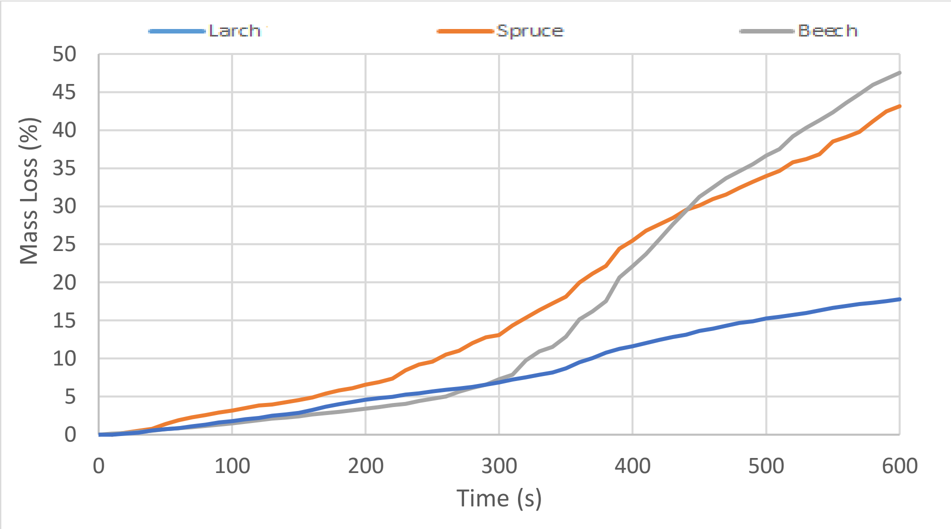


Fig. 3 The course of mass loss with time for distance of 40 mm.

The steepest course of mass loss showed curves for distance 30 mm of wood samples from emitter (fig. 4). To time of 30 second was course of curves almost the same, when the bigger mass loss showed the spruce wood with average relative mass loss $\delta_m = 81.9$ %. The biggest mass loss showed beech wood from time of about 100 seconds with an average relative mass loss $\delta_m = 87$ %. The average relative mass loss of larch wood has a value $\delta_m = 57.5$ %.

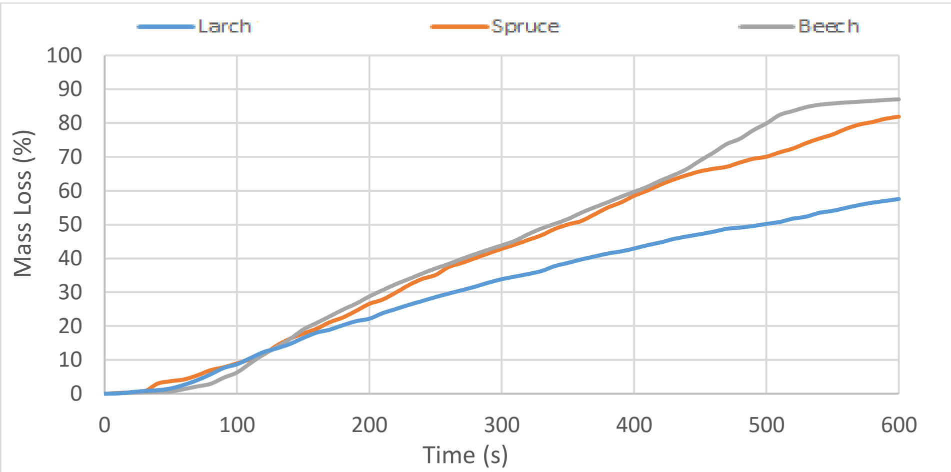
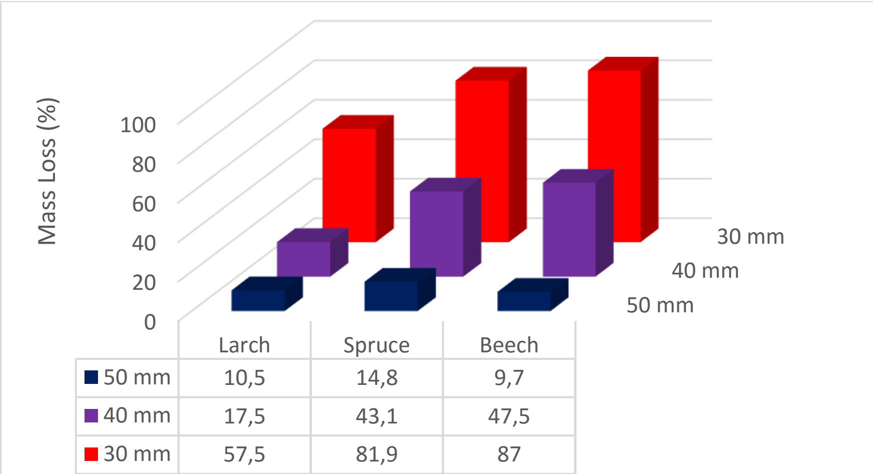


Fig. 4 The course of mass loss with time for distance of 30 mm.

At the distance of samples 50 mm from the emitter (fig. 2), especially density of tree species has had an impact on mass loss. The highest decrease reached spruce ($\rho \approx 486$ $kg \cdot m^{-3}$), a smaller mass loss reached larch ($\rho \approx 643$ $kg \cdot m^{-3}$) and the smallest mass loss reached the most densily beech wood ($\rho \approx 842$ $kg \cdot m^{-3}$). At the distance of samples of 40 mm from source of radiant heat (fig. 3) we can see the impact of chemical composition of tree species to mass loss. Curves of mass loss of spruce and beech wood had to time 310 seconds simillar pattern,then the mass loss of beech sharply increased - the highest hemicellulose content. Larch reached the lowest mass loss. At the distance of samples 30 mm from the source of radiant heat (fig. 4), chemical composition has influence to mass loss again. Beech wood with the highest hemicelluloses content showed the highest mass loss, followed by spruce wood and the lowest mass loss showed larch wood. Fig. 5 shows the mass loss of tree species in all three distances from the emitter.



	Larch	Spruce	Beech
50 mm	10,5	14,8	9,7
40 mm	17,5	43,1	47,5
30 mm	57,5	81,9	87

Fig. 5 The average total mass loss (%) of the test samples.

From comparison of the mass losses it is clear, that larch wood reached the lowest mass loss at distances of 30 mm and 40 mm from the source of radiant heat. Followed the spruce wood, and the highest mass loss had in the same terms the beech wood. Spruce wood despite a lower density have only a little lower mass loss in compared with beech wood. This phenomenon can be explained by the higher proportion of hemicellulose (47.37%), compared larch wood (32.78%) (Tab. 1). Beech wood therefore showed the lowest resistance to thermal load from among the tested tree species. Similar values in the works already recorded PETTERSEN (1984), ČABALOVÁ *et al*. (2013).

From the mass loss we expressed the relative rate of burning of selected tree species. It is true for all samples, that the relative rate of burning decreases with increasing distance from the radiant source of heat. In all cases, the relative rate of burning quickly increased to a maximum value at the distance of 30 mm from the surface of emitter. It is caused by ignition of wood.

At the distance of samples 50 mm from source of radiant heat was the lowest average rate of burning in case of beech wood (0.014 $\%\cdot s^{-1}$). A higher rate of burning showed in average larch wood (0.016 $\%\cdot s^{-1}$) and the highest average rate of burning was calculated for spruce wood (0.020 $\%\cdot s^{-1}$) at a maximum (0.025 $\%\cdot s^{-1}$).

At distance of samples 40 mm from the emitter (Fig. 7) was the lowest average rate of burning (0.017 $\%\cdot s^{-1}$) found for a larch wood. Maximum rate of burning was (0.020 $\%\cdot s^{-1}$). Higher average rate of burning was recorded in case of beech wood (0.040 $\%\cdot s^{-1}$). Its course is to 240 seconds nearly identical with the curve of spruce. then gaining steeper course and has maximum rate of burning (0.079 $\%\cdot s^{-1}$), which is also the highest value of the maximum rate of burning of all the tree species observed by us at this distance. The highest values of average rate of burning were in case of spruce wood (0.048 $\%\cdot s^{-1}$). During the first minute of the thermal load the rate of burning increase rapidly then slowly decrease and then increases again to a maximum value (0.072 $\%\cdot s^{-1}$).

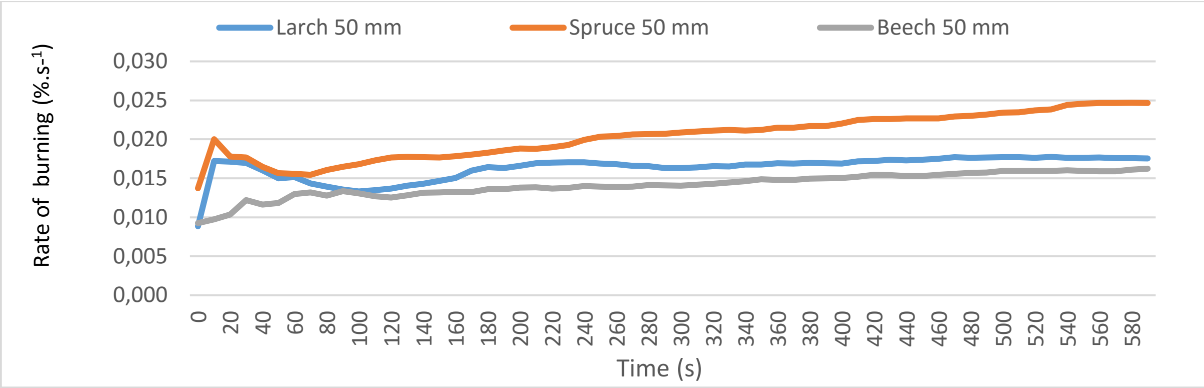


Fig. 6 Rate of burning – 50 mm distance.

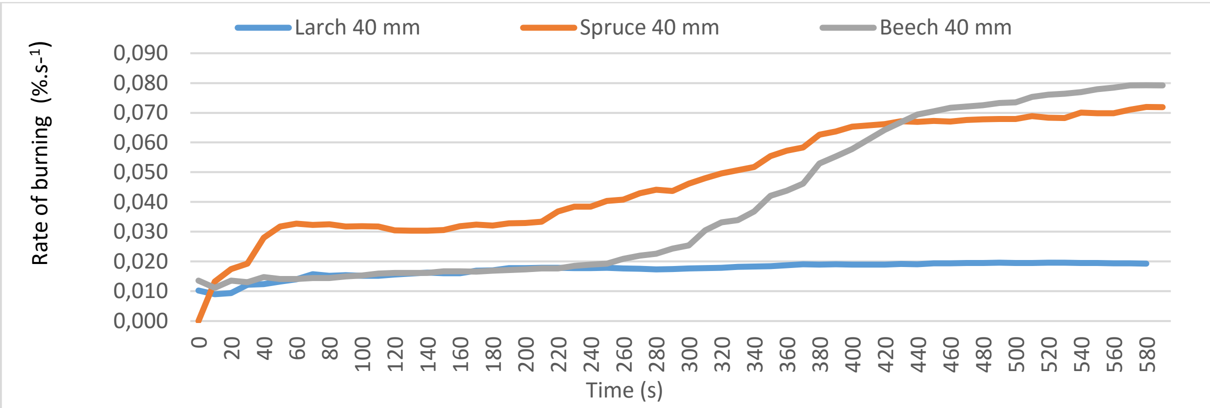


Fig. 7 Rate of burning – 40 mm distance.

The highest values of rate of burning showed samples at the distance of 30 mm from the surface of emitter (Fig. 8). In all three cases, after reaching a maximum rate of burning, became decrease of rate of burning. The lowest average value (0.098 $\%\cdot s^{-1}$) showed samples of larch wood. In case of spruce wood it occured in 20 seconds a sharp increase of rate of burning caused by a sudden ignition and the overall average value was (0.126 $\%\cdot s^{-1}$). The highest average value of rate of burning achieved beech (0.127 $\%\cdot s^{-1}$), the maximum rate of burning was recorded at time 510 seconds (0.162 $\%\cdot s^{-1}$).

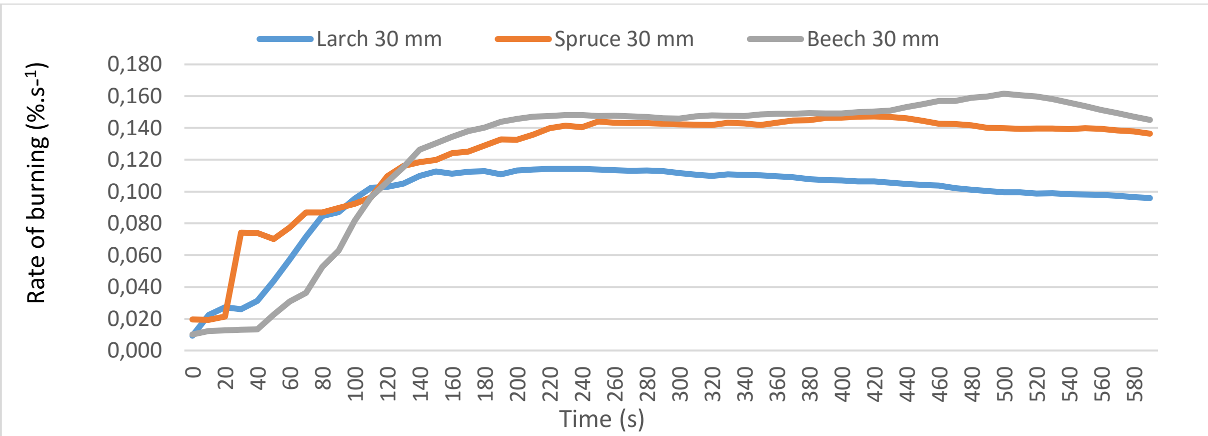


Fig. 8 Rate of burning – 30 mm distance.

The ratio of the maximum rate of burning and the time of achieved maximum rate of burning a/b is a value designed for test methods of fire protection. The ratio is multiplied by

10^6, the final values reflects the material contribution to the spread of fire (MAKOVICKÁ-OSVALDOVÁ *et al*. 2012). Tab. 2 states this ratio by the test distances. It specifies that a distance of 50 mm from the emitter has the highest contribution to the spread of fire spruce wood. At a distance of samples from the emitter of 40 mm has the highest contribution to spread of fire beech wood and at the distance of 30 mm significantly larch wood.

Tab. 2 Rate of burning, time of maximum rate of burning, ratio a/b.

Wood	l (mm)	τ_{vmax} (s)	v_{max} (%·s⁻¹)	$v_{average.}$ (%·s⁻¹)	(a)/(b)·10^6 (%·s⁻²)
Spruce	50	560	0.025	0.020	44.64
	40	590	0.072	0.048	122.03
	30	420	0.147	0.126	350.00
Larch	50	460	0.018	0.016	39.14
	40	500	0.020	0.017	40.00
	30	220	0.114	0.098	518.18
Beech	50	480	0.016	0.014	33.33
	40	580	0.079	0.040	136.20
	30	510	0.162	0.127	317.65

One of the factors of the material, which affects the rate of burning of wood is the density (BABRAUSKAS 2005). The material with the higher density is more difficult combustible, which is confirmed in case of larch and beech wood. Beech wood has a higher hemicellulose content (Tab. 1), which resulted in another curves of rate of burning. Several authors (TRAN 1992; KUČEROVÁ *et al*. 2011) have confirmed that the rate of burning is inversely proportional to the content of lignin in wood. It follows, that by estimating the trend of rate of burning changes should be taken into the states not only the density of the material, but also chemical composition. In our case is particularly true for larch wood and partly for spruce wood. The rate of burning in her studies also dealt with (MAKOVICKÁ-OSVALDOVÁ *et al*. 2012).

Char layer thickness we determined by using caliper after felling samples in half. The experiment confirmed, that the increasing of the distance of heat source from the surface of the material thickness of the char layer decreases and decreases an impact of the heat source too. Significant differences can be observed particularly between distances of 30 and 40 mm. At a distance of sample of 30 mm from the surface of emitter was formed in the case of beech wood charred layer of 100 % of the thickness of the sample, followed by spruce wood and the lowest thickness was measured for larch wood

Char layer and its thickness significantly influences the amount of lignin in wood. Most of lignin (27.22 %) and while the lowest density has a spruce, resulting in the highest proportion of the char layer. The same results published MAKOVICKÁ-OSVALDOVÁ *et al*. (2014), who by the comparing selected tree species identified coarsest charred layer for spruce. Beech wood has higher density, but also the lowest lignin content (22.57 %) and the highest content of hemicellulose (47.37 %) and reached the highest mass loss, the highest average relative rate of burning and also a high proportion of char layer. Dimensional indicators of charring wood are listed in Tab. 3.

Statistical evaluation was carried out in within the STATISTICA software such as two-factors analysis, where: *l* - the distance from the emitter, *dr* - factor of tree species, * - interaction effects. Mass loss states Tab. 4, which shows that the effect of distance from the source of radiant heat and kind of tree species is statistically significant. Statistically most significant effect on mass loss has a distance of samples from the surface of the emitter. In case of two-factorial interaction is regarded as statistically significant interaction tree species - distance from the source of radiant heat.

Tab. 3 Dimensional indicators of charring wood.

Wood	l (mm)	h_1 (mm)	h_p (mm)	h_2 (mm)	Δh (mm)	Δh (%)
Spruce	30	19.96	18.12	3.98	14.14	78.04
	40	20.02	18.95	10.97	7.98	42.11
	50	19.93	19.22	14.40	4.82	25.08
Larch	30	19.97	18.25	11.65	6.60	36.16
	40	19.98	19.53	16.01	3.52	18.02
	50	20.00	19.38	16.69	2.69	13.88
Beech	30	20.00	–	–	–	100
	40	19.98	16.88	12.64	4.24	25.12
	50	19.96	18.92	17.50	2.42	12.79

Where: l - the distance from the emitter, h_1 - thickness of the sample before thermal loading, h_p - thickness of the sample after thermal loading, h_2 - undegraded thickness of sample after thermal loading, Δh - char layer.

Tab. 4 Statistical evaluation of the impact of the considered factors for value of mass loss.

Source of oscillation	Sum of squares	Degrees of freedom	Straggling	Fisher´s F-test	P - Level of significance
Total average	62293.3	1	62293.3	922.2	0.000
dr	2893.2	2	1446.6	21.4	0.000
l	25620.2	2	12810.1	189.6	0.000
dr*l	1293.0	4	323.3	4.8	0.005
Random effect	1823.8	27	67.5		

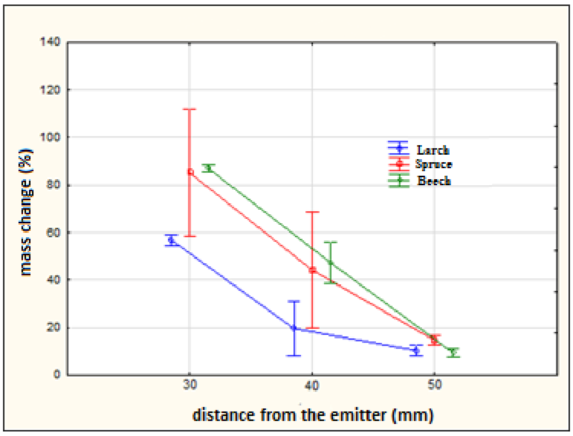


Fig. 9 Statistical evaluation of the effect of distance on mass loss.

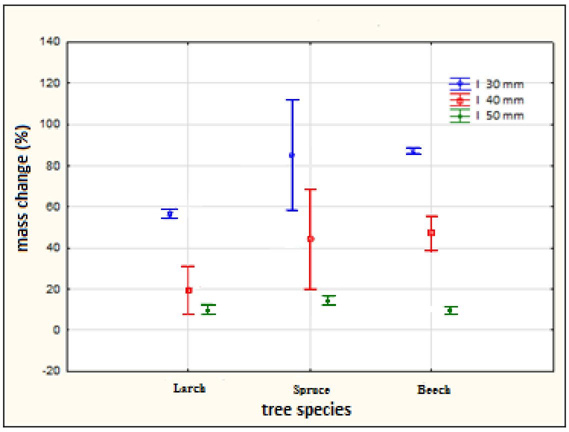


Fig. 10 Statistical evaluation of the effect of tree species on mass loss.

CONCLUSION

Experiments confirmed that the significant impact on the rate of burning and mass loss have the distance of the wood from the source of radiant heat, density ach chemical composition of tree species.

Conducted experiments confirmed that the test samples of beech at a distance of 30 mm and 40 mm from the source of radiant heat showed the higher mass loss and their resistance to thermal load was lower than in samples of spruce. Higher resistance to thermal degradation at the same distances showed, compared with beech, in spite of lower density, samples of larch.

Relative rate of burning decreases with increasing distance of the samples from the source of radiant heat. At a distance of 30 mm from the emitter reached a rate of burning a maximum value of about from 240 seconds compared with the distance of 40 mm and 50 mm, which is caused by ignition of samples.

Contribution of the tree species to the spread of fire was at the distance 50 mm and 40 mm significantly lower compared with the distance of 30 mm. At this distance it has the highest contribution to the spread of fire paradoxically larch wood.

The predominant chemical composition (lignin content) and density had a significant impact in the event of the formation of char layer of wood in the process of thermal degradation.

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