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Calorific value and fire risk of selected fast-growing wood species

Jozef Martinka[1] · **Filip Martinka**[2] · **Peter Rantuch**[1] · **Ivan Hrušovský**[1] · **Lenka Blinová**[1] · **Karol Balog**[1]

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Abstract This study deals with heat of combustion of selected fast-growing woods. The study also investigates the impact of heat flux on fire risk of the selected fast-growing woods. The hybrid poplar J-105 (*Populus nigra* × *P. maximowiczii*), white willow (*Salix alba* L.) and black locust (*Robinia pseudoacacia* L.) woods were measured. The heats of combustion were determined by a bomb calorimeter. Fire risk was evaluated with a cone calorimeter at different heat fluxes. The net heat of combustion occurred in the interval from 17.68 MJ kg^{-1} (black locust) to 18.02 MJ kg^{-1} (hybrid poplar). Fire risk was assessed on the basis of the critical heat flux, maximum average rate of heat emission, carbon monoxide yield, smoke yield and time to flashover. The hybrid poplar had the lowest critical heat flux (12.8 kW m^{-2}), and the white willow had the highest critical heat flux (17.4 kW m^{-2}). The maximum average rate of heat emission and the smoke yield increased with the increasing heat flux. On the other hand, carbon monoxide yield decreased with the increasing heat flux. The differences between the times to flashover of the measured wood species were not significant.

Keywords Calorific value · Carbon monoxide yield · Cone calorimeter · Fast-growing wood · Fire risk · Smoke yield

Introduction

Fossil fuels are currently the most important energy sources. Nevertheless, world reserves of fossil fuels are limited, and during their combustion greenhouse gases are released into the atmosphere. Due to this, there are attempts to increase the proportion of other energy sources that do not produce greenhouse gases or have zero balance of greenhouse gases. The sources that do not produce greenhouse gases or have zero balance of greenhouse gases are divided into nuclear energy and renewable energy sources.

After the Fukushima accident in the year 2011, some countries (mainly Japan and Germany) began to reduce their energy production in nuclear power stations due to which the proportion of the nuclear energy in the total amount of energy produced worldwide decreases. Hence, renewable energy sources seem to be the most promising for the future. Directive 2009/28/EC [1] of the European Parliament and of the Council considers the following renewable energy sources: wind, solar, aerothermal, geothermal, hydrothermal and ocean energy, hydropower, biomass, landfill gas, sewage treatment plant gas and biogases.

Biomass is the most important renewable energy source, which according to the International Energy Agency [2] makes 10.3% of the global energy production. In addition, biomass utilisation also reduces the energetic dependency of the European Union, and according to Sasaki et al. [3], in Japan there is a demand to replace nuclear energy with the energy produced from wood biomass.

Depending on the acquisition of energy biomass, we can talk either about energy crops, i.e., deliberately grown biomass or about waste biomass. The use of energy crops for energy production is limited by the worldwide population growth and subsequent increasing demand on food.

✉ Jozef Martinka
jozef.martinka@stuba.sk

[1] Faculty of Materials Science and Technology in Trnava, Slovak University of Technology in Bratislava, Jána Bottu 2781/25, 917 24 Trnava, Slovakia

[2] SSE - Distribution, a.s, Švantnerova 9, 975 48 Banská Bystrica, Slovakia

Hence, deliberate production of biomass for energy purposes on high-quality agricultural land seems to be less prospective. Due to this, biomass for energy purposes will be more frequently grown in the areas not suitable for the production of agricultural products (mainly wet and flooded or very dry areas). Thus, fast-growing wood species seem to have the greatest potential to be used as biomass for energy purposes, since they can maximise their annual yield per area unit in the areas unsuitable for agricultural production. The annual yield of a specific fast-growing wood species and the possibility to grow it under specific conditions depends on a number of factors. The most important factors are latitude, elevation, soil type, precipitation total (not only annual, but also monthly), occurrence of ground water, occurrence and duration of floods, and wind speed and its direction. Therefore, different fast-growing wood species are grown in different areas.

Chemical composition, physical qualities and energetic potential of fast-growing wood species have been studied by a number of scientific works, e.g., Rahmonov [4], Luo and Polle [5], Sannigrahi et al. [6], Kačík et al. [7], Stolarski et al. [8], Candelier et al. [9], Haddou et al. [10] and Naidu et al. [11]. In the listed works, the energetic potential of fast-growing wood species was determined by a bomb calorimeter or was calculated. A bomb calorimeter measures the heat of combustion from the temperature rise in the calorimeter vessel in accordance with ISO 1716 [12]. During the test that is performed following the cited standard, the sample is burnt in a calorimetric bomb filled with oxygen under pressure from 3 to 3.5 MPa. Such conditions significantly differ from real conditions during biomass combustion. Due to this, under real conditions biomass never reaches its heat of combustion measured in a bomb calorimeter. The input data required for the calculation of the biomass net heat of combustion include the content of lignin and extractives or elemental composition. The process of calculation is thoroughly described in the scientific works of Demirbas [13] and Telmo and Lousada [14]. The cited calculation procedures were based on the statistical analysis of heat of combustion values (determined by a bomb calorimeter) of different wood species and their chemical composition. They attempt to approximate the values measured in a bomb calorimeter. The conditions in a cone calorimeter (determined by oxygen consumption) resemble more the conditions of real combustion. In spite of that, only a few studies dealing with the biomass heat of combustion derived from the oxygen consumption have been published, e.g., Kamikawa et al. [15] and Martinka et al. [16]. Moreover, no study dealing with a complex research of fire risk of fast-growing wood species has been published so far.

Heat release rate is the best indicator of material fire risk [17]. To perform a complex assessment of fire risk, other information is also important apart from the heat release rate including the critical heat flux, carbon monoxide yield, smoke yield and time to flashover.

The aim of this study is to determine the gross and net heat of combustion of the following fast-growing wood species: hybrid poplar J-105 (*Populus nigra* × *P. maximowiczii*), white willow (*Salix alba* L.) and black locust (*Robinia pseudoacacia* L.). The other goal is to determine the impact of heat flux on fire risk of the selected fast-growing wood species.

Materials and methods

The research was performed on the samples of the three fast-growing wood species: hybrid poplar J-105 (*P. nigra* × *P. maximowiczii*), white willow (*S. alba* L.) and black locust (*R. pseudoacacia* L.). Hybrid poplar J-105 grew in Habartice village in the Czech Republic (GPS coordinates: 51°01′06″N 15°03′15″E) at an elevation of 237 m above sea level. White willow and black locust grew in Železná Breznica village in the Slovak Republic (GPS coordinates: 48°36′48″N 19°00′26″E) at an elevation of 430 m above sea level. Prior to the experiment, the samples were dried at 103 ± 2 °C to 0 mass% water content, and consequently they were conditioned in a desiccator at a temperature of 20 ± 1 °C during 24 h.

The content of volatile matter, fixed carbon and ash was determined in accordance with ISO 18122 [18] and ISO 18123 [19] and is shown in Table 1. The content of holocellulose, lignin and extractives is presented in Table 2. The content of holocellulose was determined according to Wise et al. [20], the content of lignin according to ASTM D1106-96 [21], and the content of extractives was determined in the mixture of ethanol and toluene according to ASTM D1107-96 [22]. The elemental composition determined using ELEMENTAR vario MACRO cube instrument is given in Table 3, and the density is in Table 4.

The gross and net heat of combustion were determined using a bomb calorimeter (supplied by IKA Werke GmbH & Co. KG, Germany). The test equipment, test procedure,

Table 1 Proximate composition of measured samples

Wood species	Fixed carbon/mass%	Ash/mass%	Volatile matter/mass%
Hybrid poplar J-105	13.3	0.3	86.4
White willow	14	0.3	85.7
Black locust	16	0.4	83.6

Table 2 Chemical composition of measured samples

Wood species	Holocellulose/ mass%	Lignin/ mass%	Extractives/ mass%
Hybrid poplar J-105	72.75	22.33	3.3
White willow	73.11	23.49	4.69
Black locust	77.67	17.64	6.56

Table 3 Elemental composition of measured samples

Wood species	C/mass%	H/mass%	O/mass%	N/mass%	S/mass%
Hybrid poplar J-105	45.8	5.37	48.53	0.12	0.19
White willow	48.19	7.33	44.21	0.17	0.11
Black locust	48.27	7.13	44.34	0.23	0.03

Table 4 Density of measured samples

Wood species	Density/kg m^{-3}
Hybrid poplar J-105	306.1 ± 6.2
White willow	366.8 ± 14.2
Black locust	652.9 ± 18.8

form and preparation of the samples were in compliance with ISO 1716 [12].

The net heat of combustion values were determined also with a cone calorimeter (supplied by Fire Testing Technology Ltd., UK). The cone calorimeter was used to quantify additional characteristics that describe fire risk of the examined wood species and the impact of their combustion on environment (critical heat flux, heat release rate, maximum average rate of heat emission, carbon monoxide yield and smoke yield, and the tendency to fire propagation in flashover phase). The cone calorimeter, test procedure, form, dimensions and the preparation of samples were in accordance with ISO 5660-1 [23]. Surface dimensions of samples (100 × 100 mm) are prescribed by ISO 5660-1 [23]. The cited standard enables to measure samples of varying thickness. The analysed samples were 50 mm thick. Prior to the test with the cone calorimeter, the surface of the samples was ground with grinding paper with 80 and 120 grain size using an abrasive-band grinding machine. During the test, the samples were oriented horizontally. The samples were analysed at three heat flux (25, 35 and 50 kW m^{-2}).

The critical heat flux was calculated from the ignition times measured with the cone calorimeter using the method of Mikkola [24]. The tendency to fire propagation in the flashover phase was determined from the data measured in the cone calorimeter (ignition time, heat release rate, and total released heat) using the methods according to Kokkala et al. [25]. Similarly, the reaction to fire class was determined from the data measured in the cone calorimeter using the method of Hansen and Kristoffersen [26].

Thermal programme of experimental methods

During the cone calorimeter test (in accordance with ISO 5660-1:2015 [23]), the samples were loaded by a constant heat flux of 25, 35 and 50 kW m^{-2} for time periods from 0 to 32 min. The exact heat fluxes on the sample surfaces together with the cone heather temperatures are shown in Table 5. The heat fluxes were calibrated by the Schmidt–Boelter radiometer.

The thermal programme of ash content determination according to ISO 18122 [18] is shown in Fig. 1. The content of the volatile matter according to ISO 18123 [19] was determined by the isothermal sample heating at a temperature of 900 ± 10 °C in the muffle furnace for 7 min.

During the gross and net heat of combustion test, the samples were ignited by a nickel wire connected to an electric current. The total energy released form the nickel wire was 27 ± 0.5 J.

Results and discussion

The gross and net heat of combustion values determined by the bomb calorimeter, and the net heat of combustion determined by the cone calorimeter are shown in Fig. 2. The net heat of combustion values measured with the cone calorimeter were lower than the net heat of combustion values determined using the bomb calorimeter. The difference is caused by the difference between the test methods. In a bomb calorimeter, the sample is burnt in the calorimeter bomb filled with oxygen under pressure of 3–3.5 MPa, while in a cone calorimeter the sample is burnt in the air with the atmospheric pressure.

The average net heat of combustion (determined with a bomb calorimeter) of the examined wood species was

Table 5 Thermal programme of cone calorimeter test

Default heat flux/ kW m^{-2}	Real heat flux/ kW m^{-2}	Cone heater temperature/°C
25	25 ± 0.5	559 ± 3
35	35 ± 0.5	639 ± 3
50	50 ± 0.5	734 ± 3

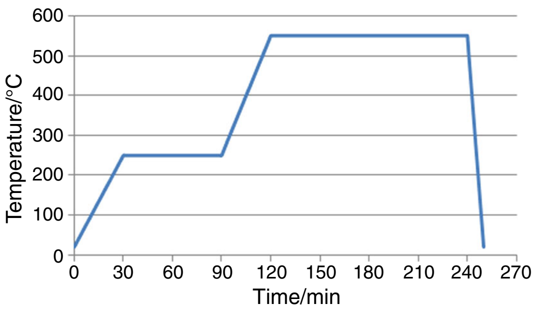


Fig. 1 Thermal programme of ash content determination

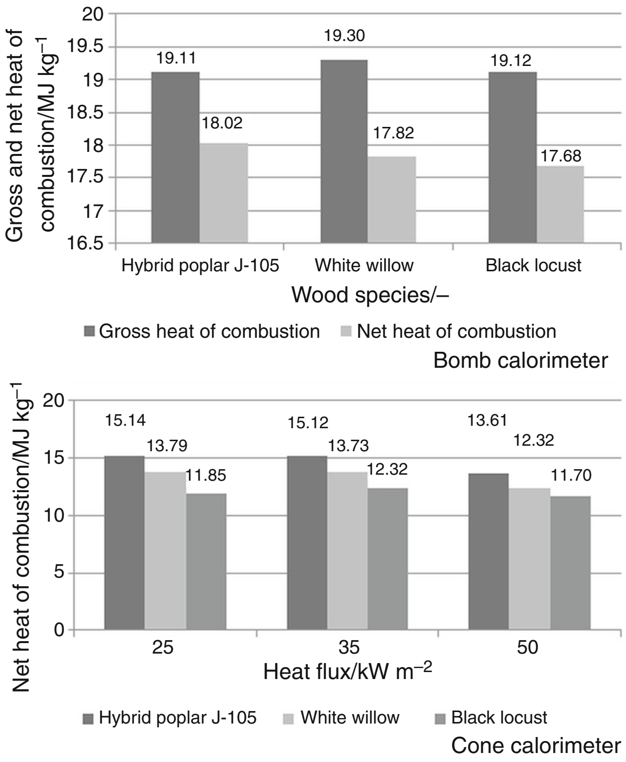


Fig. 2 Comparison of gross and net heat of combustion values of hybrid poplar, white willow and black locust determined by a bomb calorimeter and by a cone calorimeter

17.84 ± 0.17 MJ kg^{-1}. The values published by Günther et al. [27] indicated that the average net heat of combustion of wood is 17.41 ± 0.67 MJ kg^{-1}. Black locust had the lowest net heat of combustion (determined by both the bomb and the cone calorimeter). It results from the lower lignin content (in comparison with other analysed wood species). The significant impact of lignin content on the wood net heat of combustion was also confirmed by the results of Kaltschmit et al. [28] and Todaro et al. [29], who presented that the net heat of combustion of lignin was 27 MJ kg^{-1}. The net heat of combustion determined with a cone calorimeter decreases with the increasing heat flux. This is caused by the increasing release rate of gas products from thermal decomposition, which release from the sample surface to combustion zone. The increasing release rate of gas products increases the equivalent ratio of gas to oxygen in the combustion zone, which reduces combustion efficiency.

Figure 3 shows the gross heat of combustion of the analysed wood species calculated from the content of lignin and extractives using the method of Telmo and Lousada [14]. The comparison of the calculated gross heat of combustion values (Fig. 3) with the gross heat of combustion values determined with the bomb calorimeter (Fig. 2) confirmed that the calculation enables to estimate an approximate value, but does not enable its precise determination.

The values of critical heat flux are shown in Fig. 4. Hybrid poplar showed to have the lowest resistance to ignition (the lowest critical heat flux). The low value of critical heat flux of hybrid poplar results from its low density (Table 4). In contrast, white willow showed to be most resistant to ignition. Its higher resistance to ignition in comparison with black locust can be explained by a markedly higher content of lignin (Table 2) in white willow than in black locust. The obtained results are in accordance with the results of Fengel and Wegener [30], Martinka et al. [31] and Osvaldova et al. [32], who showed that the resistance of wood species to thermal decomposition increases with the increasing density and lignin content. Although the content of lignin in hybrid poplar and white willow was approximately the same, the critical heat flux of white willow was significantly higher. The critical heat flux of white willow was higher than that of black locust in spite of the lower density of white willow. The obtained data indicate that the wood species with low density (of approximately 300 kg m^{-3}) have low resistance to initiation in spite of high lignin content, and the wood species with low lignin content (below 18 mass%) showed low resistance to ignition despite their relatively

Fig. 3 Comparison of gross heat of combustion values of hybrid poplar, white willow and black locust calculated according to Telmo and Lousada [14] method

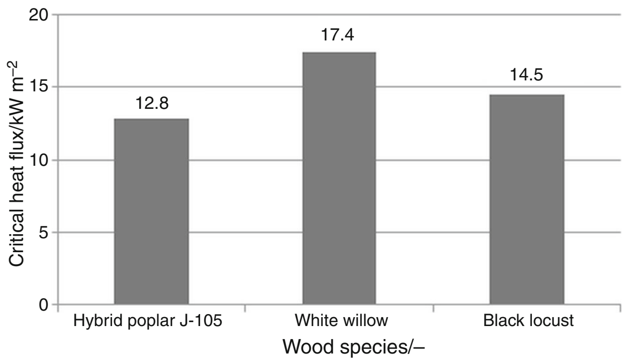


Fig. 4 Comparison of critical heat flux of hybrid poplar, white willow and black locust

high density. The data confirm that wood resistance to ignition depends more on its density than on its lignin content (chemical composition).

The comparison of the heat release rate and the maximum average rate of heat emission from the analysed fast-growing wood species loaded with different heat fluxes is presented in Figs. 5 and 6. The peak heat release rate represents the moment of sample ignition. The subsequent decrease in heat release rate is caused by the creation of a solid charred layer at the surface of the sample, which slows down overheating of the sample (caused by the heat flux from the cone emitter as well as by the back flux from the flame). The obtained data confirm that wood with higher density is less sensitive to a higher peak heat release rate due to the increased heat flux than wood with lower density. The values of the peak heat release rate and the maximum average rate of heat emission roughly correspond to the values of other types of wood and wood-based materials presented by Martinka et al. [16] and Tran [33].

Carbon monoxide yield (CO) per unit of sample mass loss or per unit of released heat decreases with the increasing heat flux (Fig. 7). In contrast, smoke yield per unit of sample mass loss or of released heat increases with the increasing heat flux density (Fig. 8). Considering the data in Fig. 2 (which confirms the decreasing combustion efficiency with the increasing heat flux), Figs. 7 and 8 shows that carbon monoxide is the main product of incomplete combustion at heat flux of 25 kW m^{-2}. In contrast, at heat flux of 50 kW m^{-2} soot is mainly produced during incomplete combustion. This conclusion is in accordance with the results of Ladomerský and Hroncová [34] and Dzurenda et al. [35].

The comparison of CO yields (per unit of mass loss or released heat) with the results of Martinka et al. [16], Karlsson and Quintiere [36] and Ozgen et al. [37] showed that CO yield from the analysed fast-growing wood species was lower than from the majority of wood species and wood-based materials.

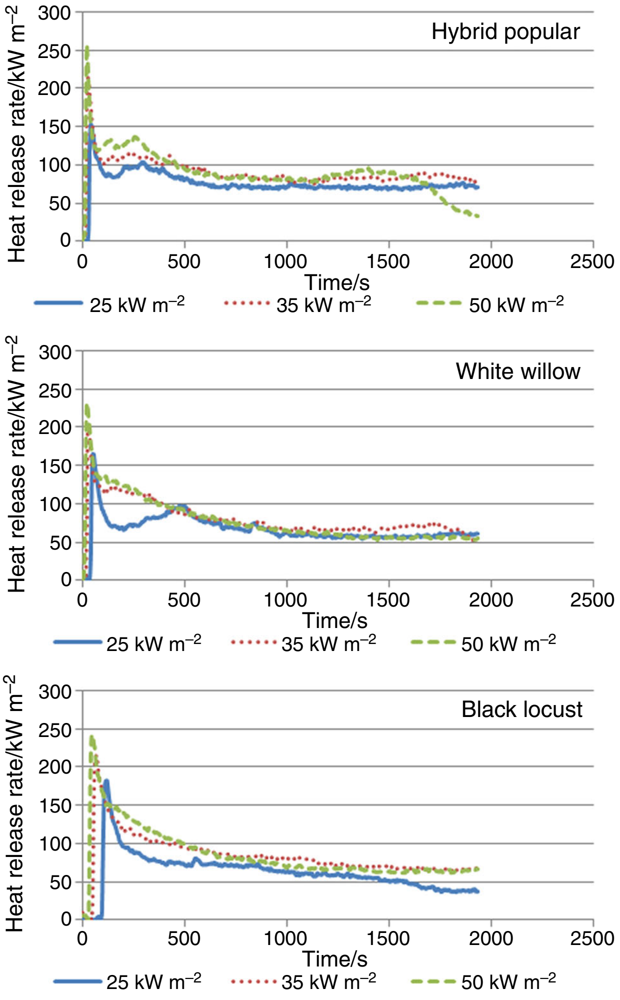


Fig. 5 Comparison of heat release rate from hybrid poplar, white willow and black locust thermally loaded with different heat fluxes

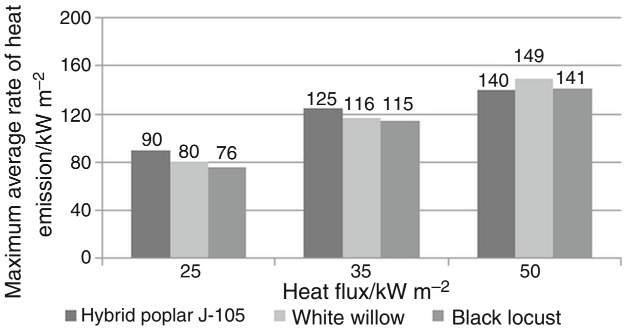


Fig. 6 Maximum average rate of heat emission from hybrid poplar, white willow and black locust thermally loaded with different heat fluxes

The relationships between the carbon monoxide yield per unit of released heat and the carbon monoxide yield per unit of sample mass loss, and between the smoke yield per unit of released heat and the smoke yield per unit of sample mass loss are shown in Fig. 9. Figure 9 proves strong

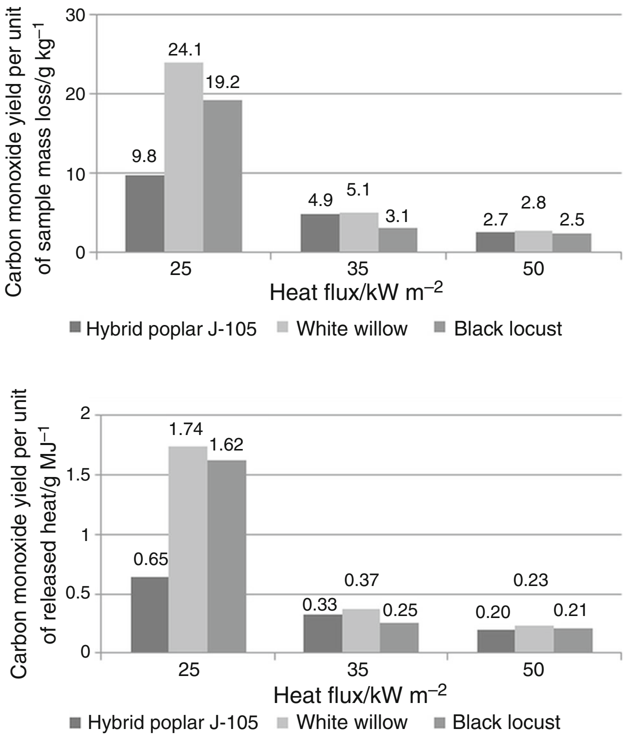


Fig. 7 CO yield (per unit of sample mass loss and per unit of released heat) from hybrid poplar, white willow and black locust thermally loaded with different heat fluxes

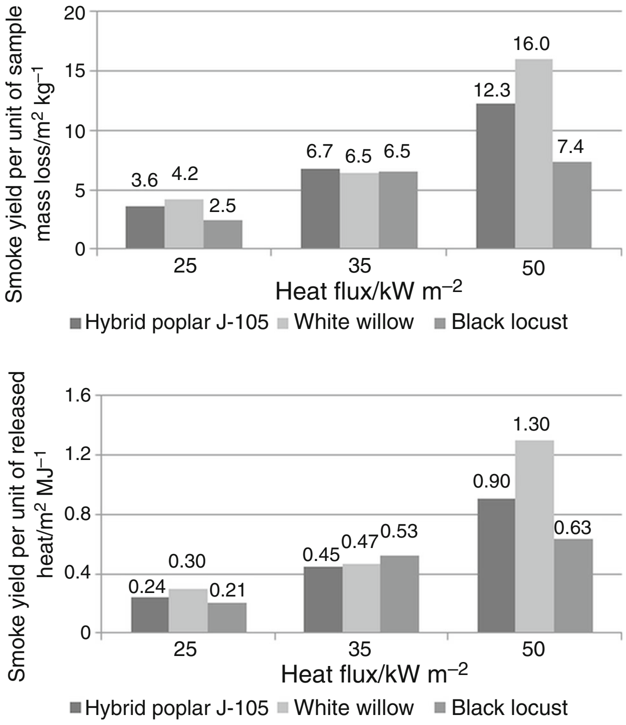


Fig. 8 Smoke yield (per unit of sample mass loss and per unit of released heat) from hybrid poplar, white willow and black locust thermally loaded with different heat fluxes

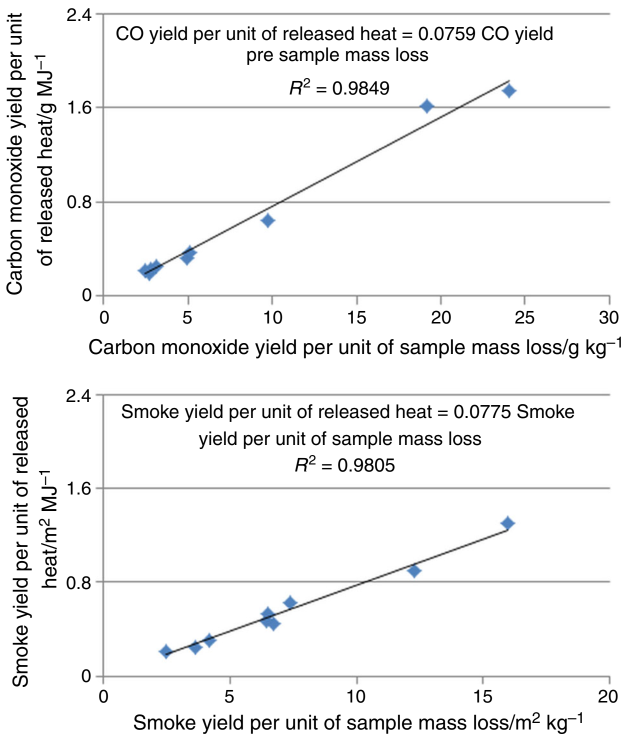
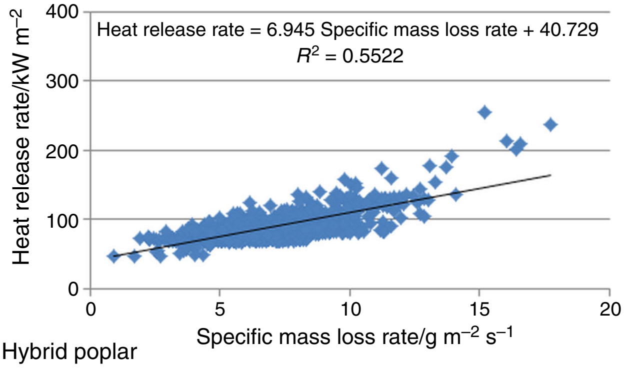


Fig. 9 Relationship between carbon monoxide yield per unit of released heat and per unit of sample mass loss and between smoke yield per unit of released heat and per unit of sample mass loss

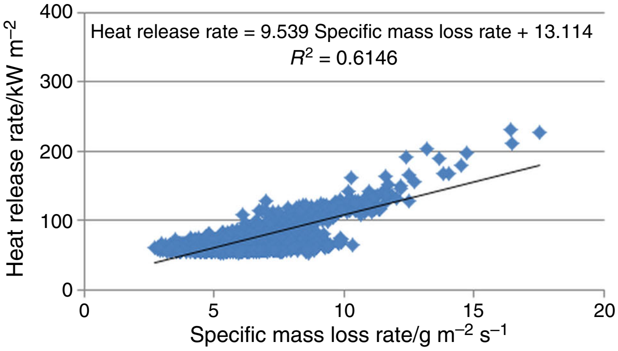
statistical dependence between the mentioned parameters (coefficients of determination R^2 are higher than 0.98). Therefore, the equations shown in Fig. 9 can be used for exact conversions between the mentioned parameters.

The statistical dependence of the heat release rate on the specific mass loss rate for the measured wood species is shown in Fig. 10. The coefficient of determination (R^2) of the statistical dependence for black locust was significantly higher than the coefficients of determination (R^2) of statistical dependences for hybrid poplar and white willow (Fig. 10). This probably results from the lower density of hybrid poplar and white willow in comparison with black locust (Table 4). Lower wood density contributed to faster formation of the charred layer on the sample surface. A typical property of the charred layer is its low mass loss rate and simultaneously relatively high heat release rate (with respect to low mass loss rate). Due to this, the coefficient of determination (R^2) for black locust was higher than for hybrid poplar and white willow.

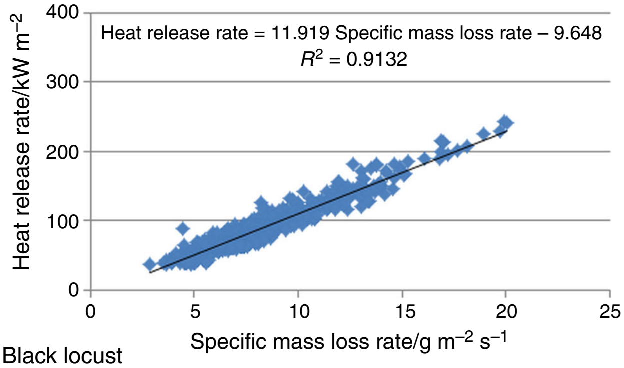
Times to flashover determined with the methods of Kokkala et al. [25] and Ostman and Tsantaridis [38] are presented in Table 6. The method by Kokkala et al. [25] was proposed to ensure its universal validity for all material types. On the other hand, the method of Ostman and Tsantaridis [38] was developed for wood and wood-based materials. Thus, the values determined by the method of



Hybrid poplar



White willow



Black locust

Fig. 10 Statistical dependence of heat release rate on specific mass loss rate of measured wood species

Table 6 Time to flashover of selected fast-growing wood species

Wood species	Time to flashover/s	
	Kokkala et al. [25]	Ostman et al. [38]
Hybrid poplar J-105	120–600	79
White willow	120–600	86
Black locust	120–600	133

Ostman and Tsantaridis [38] are more informative. The comparison of the density of the analysed wood species (Table 4) with time to flashover (Table 6) confirms that time to flashover increases with the increasing wood density, although the increase is not significant.

Table 7 Classification of reaction to fire and additional classification for smoke production of selected fast-growing wood species

Wood species	Reaction to fire	Smoke classification
Hybrid poplar J-105	C	s1
White willow	C	s1
Black locust	C	s1

The classification of the reaction of the examined fast-growing wood species to fire is presented in Table 7. The comparison of the data in Tables 2 and 4 with the data in Table 7 confirms that (within the examined interval of densities and lignin content), neither wood density nor lignin content affected the class of their reaction to fire.

Conclusions

The presented study dealt with the heat of combustion and fire risk of hybrid poplar, white willow and black locust woods. The average gross and net heat of combustion values determined with the bomb calorimeter were 19.20 ± 0.10 and 17.84 ± 0.17 MJ kg^{-1}. The average net heat of combustion determined with the cone calorimeter was 13.29 ± 1.31 MJ kg^{-1}. The net heat of combustion determined with the cone calorimeter decreased with the increasing heat flux density. The obtained data confirm that:

- The resistance of fast-growing wood species to ignition depends more on their density than on the composition of main components (mainly lignin).
- Fast-growing wood species with higher density are more resistant to the increase in the peak heat release rate due to the exposure to the increased heat flux.
- During the combustion of fast-growing wood species loaded with heat flux of 25 kW m^{-2}, carbon monoxide is the main product of incomplete combustion, while in the case of heat fluxes of 35 and 50 kW m^{-2} soot is the main product of incomplete combustion.
- Combustion efficiency of fast-growing wood species decreases with the increasing heat flux density.
- Time to ignition of fast-growing wood species increases with the increasing density, although the increase is not significant.
- The class of reaction to fire of fast-growing wood species is not dependent on their density (in the range from 306 to 652 kg m^{-3}).

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