The Combustive Heat of Thirteen Deciduous Wood Species

Bolesław Porankiewicz,[a,*] Michał Tylman,[b] Daria Wieczorek,[c]
Anita Bocho-Janiszewska,[d] Emilia Klimaszewska,[d] and Grzegorz Wieloch [e]

The heat of combustion relative to the mass, Q_m, was evaluated for 13 deciduous wood species, ranging from low to high density. The maximum and minimum values for Q_m ranged, respectively, from 19.01 kJ·g^{-1} (S_d = 7 J·g^{-1}) to 21.66 kJ·g^{-1} (S_d = 6 J·g^{-1}) for *Populus tremula* and *Alnus glutinosa* wood. The average value of the Q_m for all wood specimens evaluated in the present study was 19.93 kJ·g^{-1} (S_d = 706 J·g^{-1}), which is 1.6% higher than the value reported in the literature (Krzysik 1975). A high correlation, R = 0.99, was observed between the volumetric heat of combustion, Q_v, and wood density, D_0. No correlation was discovered among Q_m, D_0, the ash content in the wood, a_c, as well as the content of the following elements in the ash: calcium (Ca), potassium (K), magnesium (Mg), sodium (Na), silica (Si), aluminum (Al), iron (Fe), copper (Cu), manganese (Mn), sulfur (S), and phosphorus (P).

Keywords: Wood; Deciduous Species; Heat of Combustion

Contact information: a: Poznań University of Technology, Piotrowo 5, 60-450 Poznań, Poland; b: Faculty of Process and Environmental Engineering; Department of Process Thermodynamics, University of Technology, Łódź, Poland; c: Poznań University of Economics, Poland; d: Department of Chemistry, University of Technology and Humanities in Radom 26-600 Radom, ul. Chrobrego 27, Poland; e: Department of Wood Technology, Warsaw University of Life Science, Poland;
** Corresponding author: poranek@amu.edu.pl*

INTRODUCTION

Wood is the oldest renewable material used by humans for energetic purposes. Through the ages, humans have developed many ways of generating thermal energy from wood, from open fire, to house ovens, to very efficient industrial systems of wood gas and steam production. The heat from charcoal burning has been utilized since prehistoric times and still is valuable in metallurgy because of the minimal contamination by S and P. At the same time, there has been heightened interest in combustion power plants that utilize biomass as a renewable energy source (creating competition for the particle and fiber board industries). Wood combustion is not accompanied by the melting of ash into slag. In developing countries, the use of wood for heat generation is still several times larger than in industrialized countries (Ashby and Jones 1996). Burning wood from fast-growing tree species, such as poplar and willow, as well as wood of other species, branches, and industrial waste (primarily in the form of briquettes and pellets) for energetic purposes can be a sufficient alternative to burning fossil fuels (which are non-renewable). However, some people believe wood is too valuable to be burned in any form (Hubbe 2008).

The values of heat of combustion (Q_m) reported by different authors for the same wood species (Table 1, Fig. 1) are very different. For example, the values reported for *Fagus sylvatica* range from 18.89 to 21.46 kJ·g^{-1}.

Table 1. The Heat of Combustion, Q_m, of Wood of Examined Wood Species According to the Literature

	a)	b)	c)	d)	e)	f)	g)	h)	i)
	Q_m (kJ·g^{-1})								
A	18.98	18.36	-	-	-	-	-	-	-
B	19.18	-	-	-	21.45	-	-	-	18.45[i&]
C	19.13	19.74	-		-	19.59	20.34	-	19.98[i*]
D	19.79	19.17	-	-	-	-	-	-	-
E	18.89	19.74	19.96	20.24	21.46	-	-	-	-
F	20.57	-	-	-	-	-	-	-	-
G	19.39	18.25	-	-	-	-	-	-	-
H	-	20.22	-	-	21.47	-	19.63	17.9	-
I	-	-	-	-	-	19.66	-	18.5	-
J	19.78	19.43	-	-	-	-	20.42	-	-
K	20.09	-	-	-	-	-	-	-	-
L	-	-	-	-	-	-	20.01	-	-
M	19.28	-	18.64	-	-	-	-	-	19.63[i#]

A - *Carpinus betulus*; B - *Robinia pseudoacacia*; C - *Quercus robur*; D - *Fraxinus excelsior*; E - *Fagus sylvatica*; F - *Ulmus campestris*; G - *Acer pseudoplatanus*; H - *Betula verrucosa*; I - *Acer platanoides*; J - *Alnus glutinosa*; K - *Tilia cordata*; L - *Populus tremula*; and M - *Populus nigra*. References according to Krzysik (1975): [a)] Fecher; [b)] Fabricius; [c)] Krzysik and Orlicz; [d)] Kathny; [e)] Landolt and Börnstein, [f)] Schläpfer; [g)] Wanin (1949); [h)] Björn *et al.* (2012); [i&)] Karaszkiewicz (2008); [i*#)] White (1987); [i*)] for *Quercus rubra*; and [i#)] for *Liriodendron tulipifera*

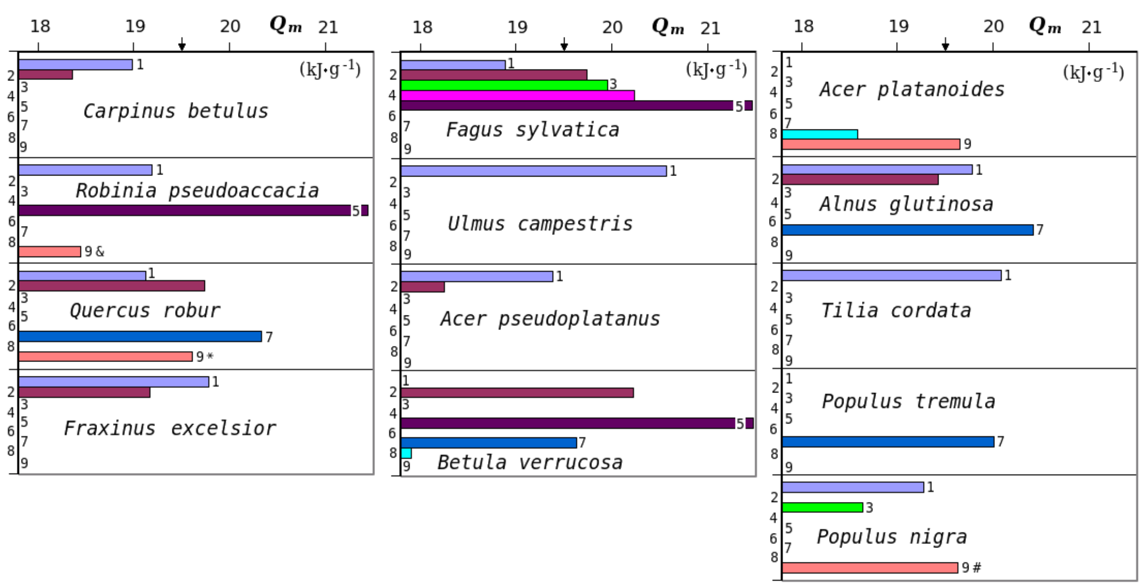

Fig. 1. Heat of combustion, Q_m, according to literature. Statistics according to Krzysik (1975): 1 –Fecher; 2 – Fabricius; 3 - Krzysik and Orlicz; 4 – Kathny; 5 - Landolt and Börnstein; 6 - Schläpfer; 7 - Wanin (1949); 8 - Björn *et al.* (2012); 9[&] - Karaszkiewicz (2008); 9[*#] - White (1987): [*]-for *Quercus rubra*, [#]-or *Liriodendron tulipifera*

The reason for the high degree of variation lies in the combined influence of tree genetics and growing conditions, resulting in different content of combustible chemical compounds present in the wood. The average Q_m value for all 13 of the wood species reported in the literature (Wanin 1949; Krzysik 1975; Björn *et al.* 2012) was 19.49 kJ·g^{-1} (S_d = 728 J·g^{-1}). The calculated results for Q_m, reported by Wojciechowska (1985) for beech, birch, oak, alder, and aspen, are lower than those presented in Table 1. Because in this work the wood was examined together with bark, the results of Wojciechowska (1985) were not taken into account in the survey. The results reported by Karaszkiewicz (2008) for black locust are lower than the Q_m reported by Fecher, as well as Landolt and Börnstein, as reported by Krzysik (1975). The absolutely dry wood density (D_0) was not evaluated in the works cited above.

Wood is comprised of natural polymers, namely cellulose, lignin, and polysaccharides (Table 2), which also contain small amounts of other substances such as tannins, fat, and starch. These substances, called extracts, are not present in all wood specimens, and vary in amount. All of these compounds consist of roughly 50% carbon (C), 44% oxygen (O), and 6 % hydrogen (H). Looking at the content of cellulose, c_c, (Table 2, Fig. 3) it can be seen that maximum values of the c_c are reported for low density trees of *Populus nigra* and *Tilia cordata*, while maximum values of the c_c for hard woods are lower.

Table 2. Content of Ash, a_c, Cellulose, c_c, Lignin, c_l, and Polysaccharides, c_p, According to the Literature

Wood species		a_c[1)]	c_c[1)]	c_l[1)]	c_p,[1)]
		(%)			
Carpinus betulus L.	Hornbeam	0.47	43	19.3-22.5	27
Robinia pseudoacacia L.	Black Locust	0.33	40.6-46.3	28.8-29.1	21.3-22.3
Quercus robur L.	Oak	0.27	39.5-42.8	24.9-34.3	19-25.5
Fraxinus excelsior L.	Ash	0.07	44.2-46.8	21.3-30.4	22.6-26.7
Fagus sylvatica L.	Beech	0.3-1.2	33.7-46.4	11.6-22.7	17.8-25.5
Ulmus campestris L.	Elm	0.75	43	27.3	21.8
Acer pseudoplatanus L.	Sycamore	0.37	38.3	25.3	20.3
Betula verrucosa Ehrh.	Birch	0.39	45.3	19.6-28.2	23.6-27.1
Acer platanoides L.	Maple	-	41.5[2)]	23.1[2)]	25.6[2)]
Alnus glutinosa L.	Alder	0.48-0.64	39.6-46.5	22.6-25.8	18.8-25.1
Tilia cordata Mill.	Linden	0.5-1.5	43.2-54	18.3-29.3	20.4
Populus tremula L.	Aspen	0.28-0.36	47.1-62.8	18.2-26.4	17.6-27.5
Populus nigra L.	Poplar	0.3-0.8	31-60	13.8- 24.5	15-23

[1)] Wagenführ and Scheiber (1974); [2)] Institute of Wood Technology, Poznań, Poland

Looking at the content of lignin, c_l, in the wood it can be noted that the largest maximum c_l value for the hard and dense wood of *Quercus robur* averaged 34.3 %, which does not refer to wood of *Carpinus betulus* (Table 3, Fig. 3). According to the work of Krzysik (1975), the polysaccharide content, c_p, consists of approximately 86% pentozans (xylan and araban) and 14 % hexozans (galactan and fructan) for deciduous wood species. For this study, the polysaccharide content's range of variation was from 15% to 28% (Table 2, Fig. 3).

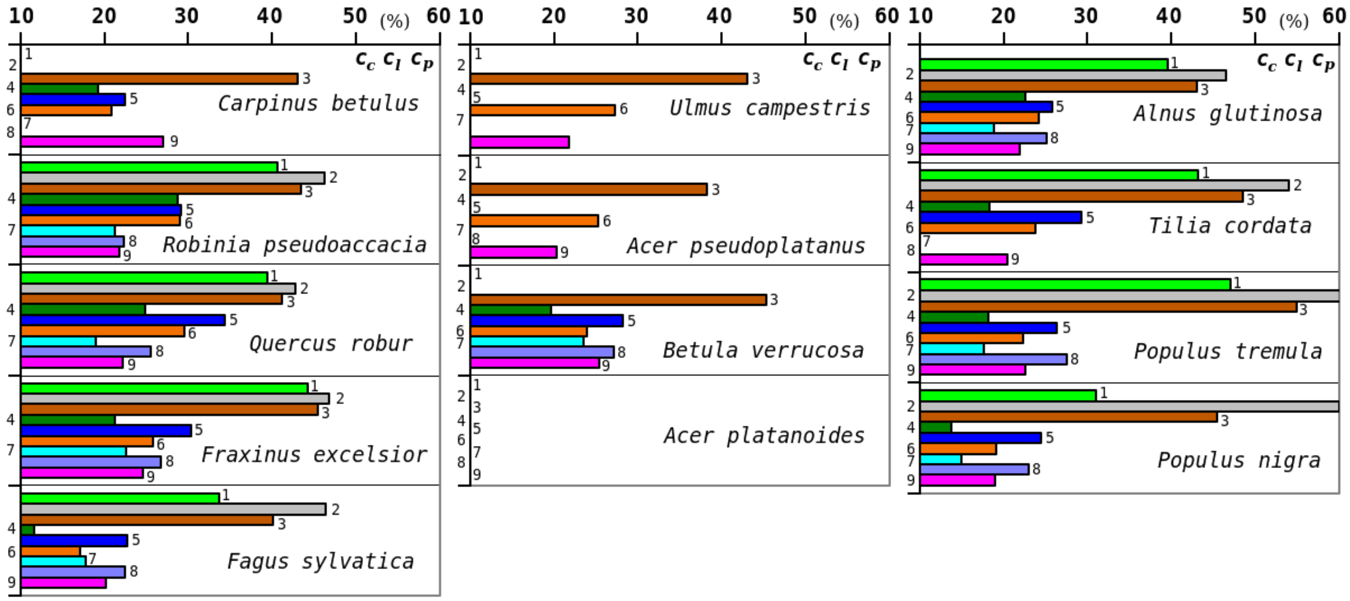

Fig. 2. Content of: 1, 2, 3 - cellulose, c_c; 4, 5, 6 - lignin, c_l; 7, 8, 9 - polysaccharides, c_p; 1, 4, 7 - minimum, 2, 5, 8 - maximum, 3, 6, 9 - average; according to Wagenführ and Scheiber (1974)

Wood can be burnt at temperatures above 1000 °C to produce carbon dioxide and water, leaving a small amount of ash containing Ca, K, and Mg and low amounts of other elements (Al, Cu, Fe, Mn, Na, P, S, and Si). At lower temperatures, the burning process is accompanied by pyrolysis, generating flammable substances like CO, CH_4, creosote, and more than 100 different hydrocarbons, as well as charcoal.

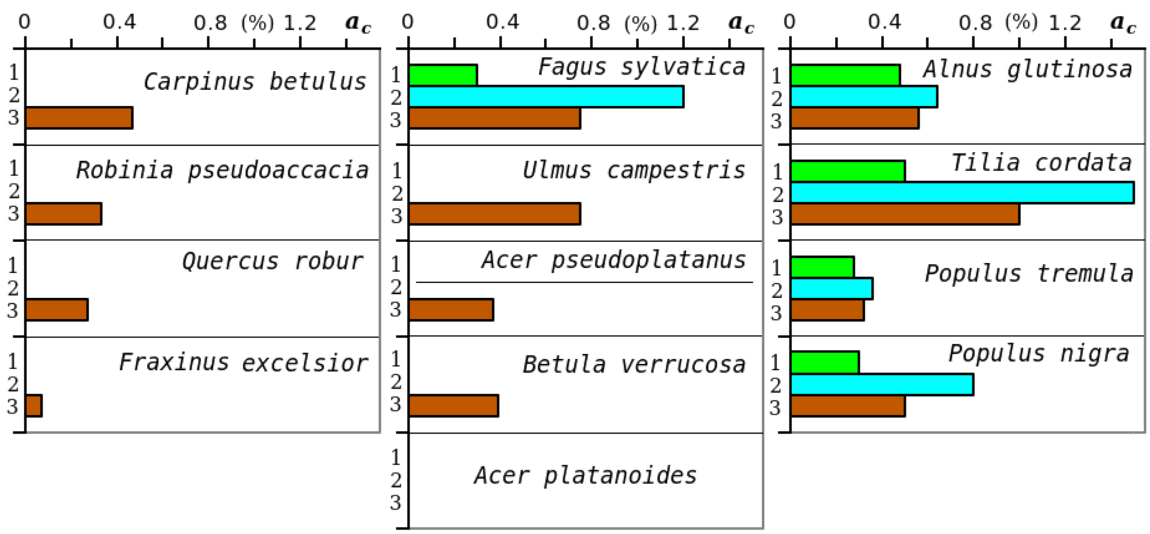

Fig. 3. Content of ash, a_c, according to Wagenführ and Scheiber (1974): 1 - minimum; 2 - maximum, 3 – average

Depending on the degree of comminution, amount of oxygen, and burning temperature, the exothermal degradation reaction of wood can proceed in different ways. Deciduous wood species, especially species with high densities, are considered to be more suitable for burning in fireplaces. These wood species do not contain natural resin. The burning of natural resin (present in the wood of coniferous species) is accompanied by the creation of carbon black, causing unfavorable embedding in chimney flues. The content of ash, a_c, (Table 2, Fig. 3) also differs significantly between wood species, ranging on average from 0.07% to 1% for *Fraxinus excelsior* and *Tilia cordata*, respectively. The reported range of a_c dispersion for *Fagus sylvatica* wood is even larger, ranging from 0.3% to 1.2. The average a_c published in the literature (Wagenführ and Scheiber 1974) seems to not be correlated with the Q_m value shown in Table 1 and in Fig. 1. The results of the a_c reported by Wojciechowska (1985) for beech, birch, oak, alder, and aspen were not taken into account in the survey, as the analysis was performed exclusively for wood with bark.

As can be seen in Table 3, lignin has the largest heat of combustion, Q_m, with a dispersion of 5.9%. In the work of White (1987), a correlation ($R^2 = 0.7$) between the Q_m and content of lignin, c_l, in the wood (red oak, maple, yellow poplar, basswood, spruce, redwood, Western red cedar, and redwood) was reported. After removing extracts from wood, an even larger correlation ($R^2 = 0.97$) was obtained in this work. The heat of combustion, Q_m, for cellulose, is clearly lower than lignin, by a larger dispersion of 34.2%. The Q_m, of the polysaccharides is within range of a typical value for cellulose.

Table 3. Heat of Combustion, Q_m, ($kJ \cdot g^{-1}$) of Components of Wood According to the Literature

Lignin	25.54[1)]	25.5[2)]	27[3)]	18.1 - 22.5[4)]
Cellulose	17.38 - 22.82[1)]	17 - 17.5[2)]	17.3[3)]	
Polysaccharides			16.2[3)]	
Extracts				3.8 - 6.4[4)]

[1)] according to Krzysik (1975); [2)] Kienzle *et al.* (2001); [3)] Kaltschmidtt (2009); [4)] White (1987)

Table 4. The Wood Density, D_0, According to the Literature

Wood species		D_0 ($kg \cdot m^{-3}$)	
Carpinus betulus L.	Hornbeam	770[1c)]	500[2a)]-820[2b)]-790[2c)]
Robinia pseudoacacia L.	Acacia	750[1c)]	620[2a)]-810[2b)]-720[2c)]
Quercus robur L.	Oak	690[1a)]-740[1b)] 640[3)]	390[2a)]-930[2b)]-650[2c)]
Fraxinus excelsior L.	Ash	710[1c)]	410[2a)]-820[2b)]-650[2c)]
Fagus sylvatica L.	Beech	660[1a)] - 720[1b)]	490[2a)]-880[2b)]-680[2c)]
Ulmus campestris L.	Elm	650[1c)]	440[2a)]-820[2b)]-640[2c)]
Acer pseudoplatanus L.	Sycamore	630[1c)]	480[2a)]-750[2b)]-590[2c)]
Betula verrucosa Ehrh.	Birch	570[3c)]	460[2a)]-800[2b)]-610[2c)]
Acer platanoides L.	Maple	-	520[4a)]-770[4b)]-620[4c)]
Alnus glutinosa L.	Alder	510[1a)] - 530[1b)] 430[3c)]	450[2a)]-600[2b)]-510[2c)]
Tilia cordata Mill.	Linden	-	320[2a)]-560[2b)]-490[2c)]
Populus tremula L.	Aspen	370[3c)]	360[2a)]-560[2b)]-450[2c)]
Populus nigra L.	Poplar	450[1c)]	370[2a)]-520[2b)]-410[2c)]

[1)] Feher after Krzysik (1975); [2)] Wagenführ and Scheiber (1974); [3)] Wanin after Krzysik (1975); [4)] Institute of Wood Technology, Poland; [a)] minimum, [b)] maximum, [c)] average

From Table 4 and Fig. 4, wide range of variation of the average wood density, D_0, between wood species can be observed, ranging from 410 kg·m^{-3} to 790 kg·m^{-3} for *Populus nigra* and *Carpinus betulus*, respectively. An even larger variation can be seen for *Quercus robur*, ranging from 390 kg·m^{-3} to 930 kg·m^{-3}.

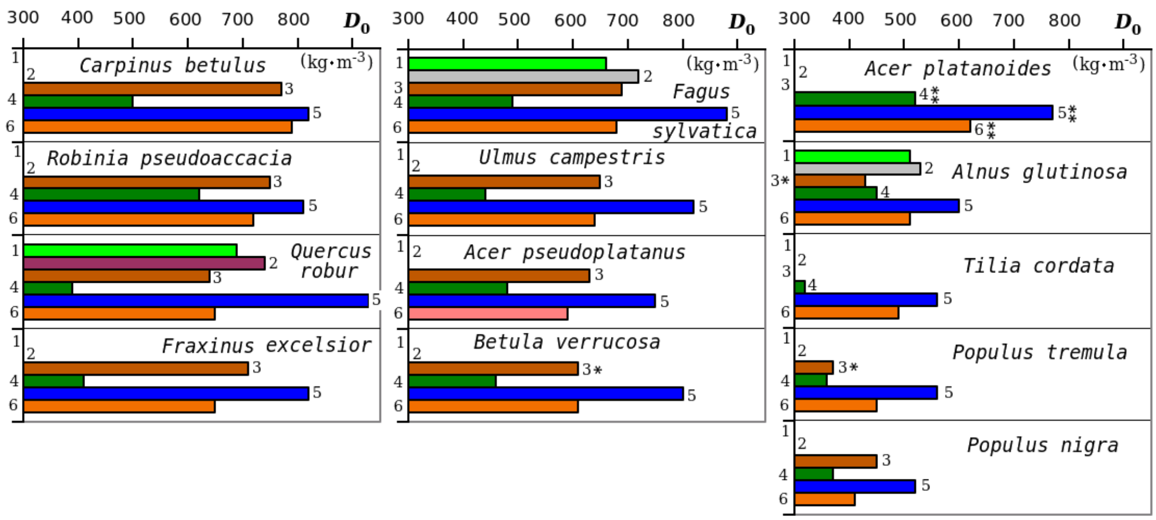

Fig. 4. Density, D_0, according to literature; 1, 2, 3: Feher after Krzysik (1975); 4, 5, 6: Wagenführ and Scheiber (1974); Wanin (1949) after Krzysik (1975): * - Wanin (1949) after Krzysik (1975); ** - Institute of Wood Technology, Poland; 1, 4 - maximum; 2, 5 - minimum; 3, 6 - average

It can be seen in Table 4 and Fig. 5 that neither *Carpinus betulus*, having the largest D_0, nor *Populus nigra*, having the lowest D_0, did the heat of combustion, Q_m, (related to wood mass) record the maximum or minimum values. The Q_m seems to not be correlated with all the wood properties discussed above. For this reason, the literature reports the common value of the Q_m for deciduous wood species as 19.61 kJ·g^{-1}.

For some wood species (*Ulmus campestris*, *Tilia cordata*, and *Populus tremula*) there is information available regarding the heat of combustion, Q_m, from only one author. For another 4 species (*Carpinus betulus*, *Fraxinus excelsior*, *Acer pseudoplatanus*, *Populus nigra*) only two authors have reported information on the heat of combustion, Q_m. Furthermore, there is missing information for the Q_m, D_0, and the a_c, for *Acer platanoides* (Wagenführ and Scheiber 1974; Krzysik 1975).

In the literature there has been no report of the densities, D_o, of the analyzed wood specimens, for which the Q_m were evaluated, and the values of volumetric heat of combustion, Q_v, were omitted as well (Krzysik 1975; White 1987; Karaszkiewicz 2008; Björn *et al.* 2012).

The goal of the present study was to evaluate the heat of combustion for 13 deciduous wood species, including *Acer platanoides* (originating from Poland), for known wood densities, D_0, and the ash content, a_c, as well as to their check correlation with chosen wood properties.

EXPERIMENTAL

Figure 5 shows clear wood of the 13 deciduous specimens examined in the present study. All specimens originated from central Poland, which has a moderate climate zone.

Fig. 5. Perpendicular to wood grains section of 13 wood species examined: 1 - *Carpinus betulus*; 2 - *Robinia pseudoacacia*; 3 - *Quercus robur*; 4 - *Fraxinus excelsior*; 5 - *Fagus sylvatica*; 6 - *Ulmus campestris*; 7 - *Acer pseudoplatanus*; 8 - *Betula verrucosa*; 9 - *Acer platanoides*; 10 - *Alnus glutinosa*; 11 - *Tilia cordata*; 12 - *Populus tremula*; 13 - *Populus nigra*

During the evaluation of the combustion heat, Q_m, of the wood specimens, a computer controlled KL12Mn calorimeter was used (http://www.precyzja.pl /produkty/kategorie/kalorymetry/kalorymetr-kl12), having the following characteristics: volume of combustion chamber, 0.34 dm^{-3}; mass and pressure of the oxygen inside the combustion chamber, 3.025 mol and 19.62 MPa, respectively; mass of cooling water in the calorimeter, 4.4 kg; and the measurement accuracy of the temperature, 0.001 ^{0}K. The calibration of the KL12Mn calorimeter was conducted for five sample weights of 1 g of benzoid acid (Q_m = 26.477 kJ$\cdot$g^{-1}). Weighting was shepherded with the use of a WAS100/X balance, manufactured by Radawag (Radom, Poland), with an accuracy of 0.0001 g. The wood specimens were prepared in fine powder form, without thick particles, obtained with use of a rasp. The wood specimens were dried out to an absolutely dry state in a drying chamber, at a temperature of 120 °C, for 10 h. The dry wood specimens were stored in a desiccator under dry silica gel. The heat of combustion was evaluated for 0.5 g of absolutely dry wood in three repetitions. The average water temperature increase in the calorimeter after burning wood specimens ranged from 0.5 to 0.9 K. The time of measurement for wood specimens weighing 0.6 g was recognized by the calorimeter as incompatible. The tests that rendered incomplete burning were rejected.

The density of wood in an absolute dry state, D_0, was evaluated with application of a weight and use of a laboratory drying chamber. The wood specimens were dried at a temperature of 105 °C, until the mass change was less than 0.001 g, which lasted about 30 h. After cooling down in a desiccator under dry silica gel, the wood specimens were weighted within an accuracy of 0.0001 g. The dimensions of wood specimens, in an absolutely dry state, were evaluated using a slice caliper with an accuracy of 0.05 mm. The ash content, a_c, in the specimens was evaluated after the wood was absolutely dry. The wood burning process was conducted in a muffle oven, at a temperature of 500 °C.

The ash was analyzed using a scanning electron microscope equipped in an energy dissipative spectrometer EDAX, type Genesis XM 2i, equipped with a nitrogen-free EDAX Apollo 10 detector FEI Quanta 250 FEG, manufactured by FEI Inc., Eindhoven, The

Netherlands, with the energy dispersive X-ray analysis detector EDAX Genesis XM 2i, manufactured by AMETEK, Inc., Philadelphia, U.S.A., in regards to elemental composition. The EDAX measurements were performed in five repetitions. The ash's carbon and oxygen content were not taken into account.

The statistical analysis was performed by calculating the average value, standard deviation, S_d, coefficient of variation, c_v, and correlation coefficient, R. The combustion values, Q_m, wood density, D_0, and ash content, a_c, were compared with the data from other works (Wagenführ and Scheiber 1974; Krzysik 1975).

RESULTS AND DISCUSSION

The results for the combustion heat, Q_m, in relation to the absolutely dry mass of wood specimens, the wood density, D_0, the content of ash, a_c, and the moisture content, m_c, of the present study are collected in Table 5. The maximum and minimum values for Q_m, ranged from 21.66 kJ·cm^{-3} (S_d = 6 J·g^{-1}) to 19.01 kJ·g^{-1} (S_d = 7 J·g^{-1}), respectively, for *Populus tremula* and *Alnus glutinosa* wood. The average value of the Q_m evaluated for all wood specimens examined averaged 19.93 kJ·g^{-1}, which is 1.6 % higher than value reported in the literature (Krzysik 1975). The standard deviation, S_d, evaluated for the Q_m, for all wood species was as high as S_d= 706 J·g^{-1}, with a coefficient of variation c_v= 3.5 %. Maximum, minimum, and average values of the Q_m in the present study are different than the values reported in the literature (Krzysik 1975). Table 5 and Fig. 6 show that values of the Q_m, observed in the present study are greater than those reported in the literature (Krzysik 1975) for *Carpinus betulus*, *Quercus robur*, *Fraxinus excelsior*, *Acer platanoides*, *Populus tremula*, and *Populus nigra*. However, for *Robinia pseudoacacia, Fagus sylvatica, Ulmus campestris, Betula verrucosa, Alnus glutinosa* and *Tilia cordata*, the values of Q_m are lower.

Table 5. The Heat of Combustion, Q_m and Q_v, the Wood Density, D_0, the Content of Ash, a_c, and the Moisture Content, M_c, of the Examined Wood

	Q_m^1	Q_m^2	Q_m^3	Q_m	D_0	Q_v	a_c	m_c
	(kJ·g^{-1})				(kg·m^{-3})	(kJ·cm^{-3})	(%)	
A	20.17	20.06	20.23	20.16	797	16.06	0.793	6.8
B	20.12	20.19	20.08	20.13	683	13.75	0.375	7
C	19.90	19.99	19.86	19.92	701	13.96	0.202	7.6
D	20.43	20.51	20.44	20.46	524	10.72	0.561	7.2
E	19.62	19.68	19.57	19.65	595	11.69	0.726	6.9
F	19.64	19.69	19.66	19.66	499	9.81	0.575	6.9
G	19.95	19.92	20.06	19.97	607	12.12	0.418	6.9
H	19.59	19.18	19.17	19.31	494	10.17	0.332	6.3
I	19.67	19.68	19.64	19.67	555	10.91	0.46	7
J	19.06	18.94	19.03	19.01	526	10	0.585	6.7
K	20.01	20.08	20.03	20.04	473	10.06	0.528	6.7
L	21.64	21.81	21.51	21.66	473	10.24	0.461	5.8
M	19.59	19.61	19.57	19.59	368	7.04	0.57	6.4

A - *Carpinus betulus*; B - *Robinia pseudoacacia*; C - *Quercus robur*; D - *Fraxinus excelsior*; E - *Fagus sylvatica*; F - *Ulmus campestris*; G - *Acer pseudoplatanus*; H - *Betula verrucosa*; I – *Acer*; J - *Alnus glutinosa*; K - *Tilia cordata*; L - *Populus tremula*; M - *Populus nigra*; $^{1, 2, 3}$ - values observed for separate measurements

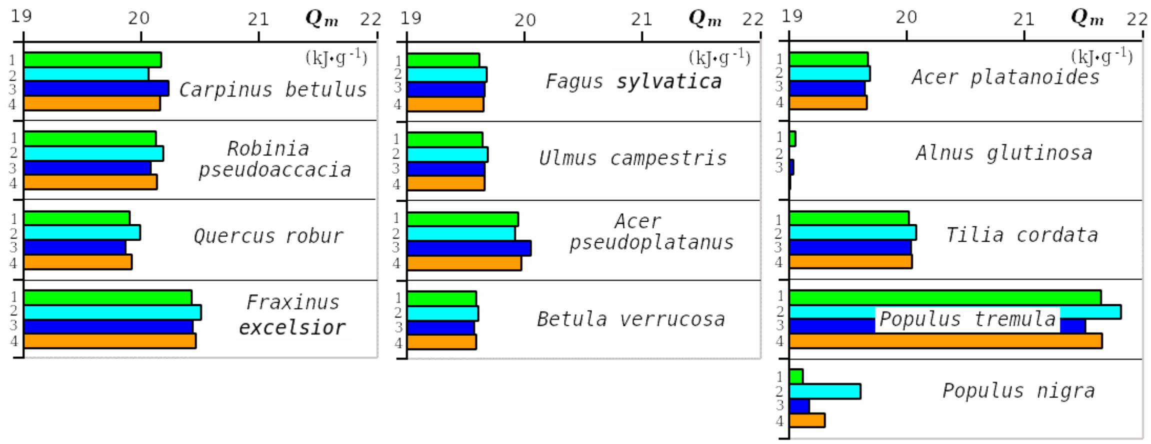

Fig. 6. Heat of combustion, Q_m, of wood specimens analyzed: 1, 2, 3 - subsequent values; 4 - average values

The disparity among the wood species can be attributed to the different amounts of combustible compounds present in the wood in both cases. Looking at Table 4 and Table 5 it can be noticed that the data reported in the literature (Krzysik 1975) and results of the present study differ (on average approximately 2%), with maximum and minimum differences of 8.2% and 0.2% for *Populus tremula* and *Tilia cordata*, respectively. It can also be seen from Table 5 and Fig. 7 that the observed wood density, D_0, falls within the range reported in the literature (Wagenführ and Scheiber 1974; Krzysik 1975) for most of the wood species examined, with the exception of *Populus nigra* and *Acer pseudoplatanus* for which no value was reported, as well as *Fagus sylvatica,* for which the D_0, is lower.

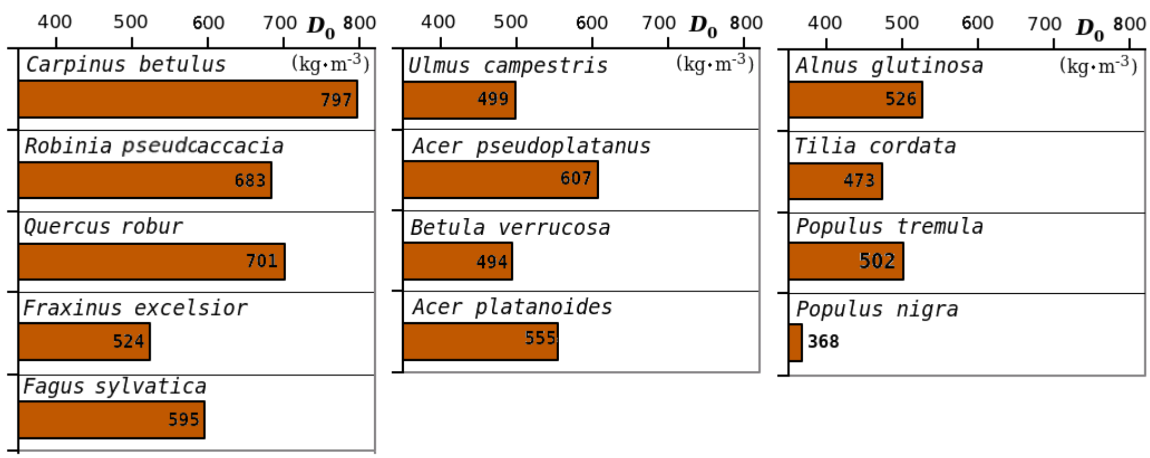

Fig. 7. Density, D_0, of wood specimens examined in the present study

No reasonable correlation (R = 0.2) between Q_m and D_0 was found during the undertaking of the present study. The Q_m value for *Acer platanoides,* missing in the literature (Krzysik 1975), was 19.97 kJ·g^{-1}. This value was larger than for *Acer pseudoplatanus*, by as much as 1.6 %. The D_0 and the a_c values for *Acer platanoides* were larger (9.4 % and 10 %, respectively) than values for *Acer pseudoplatanus*.

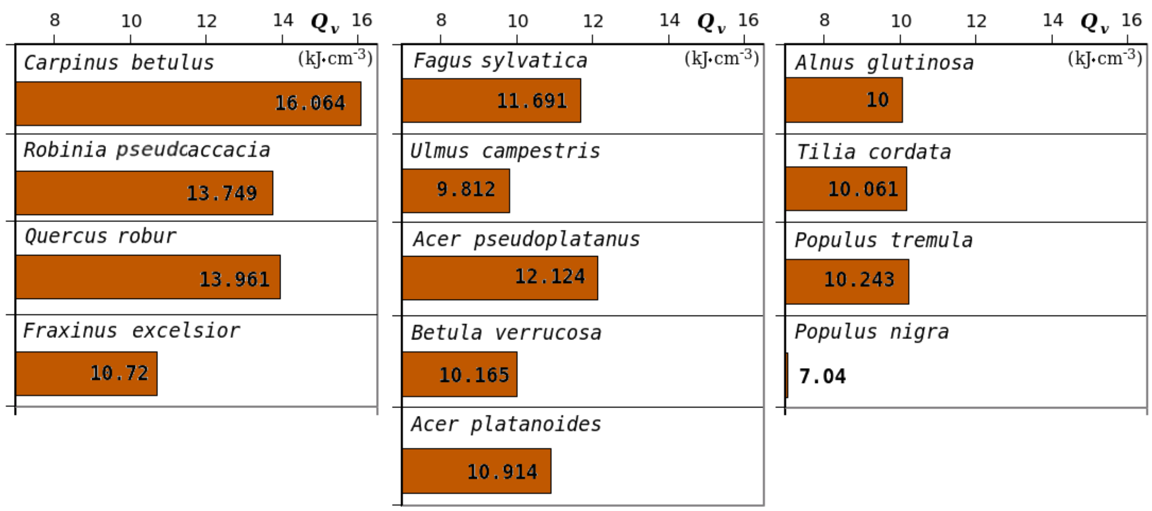

Fig. 8. Volumetric heat of combustion, Q_v of wood specimens examined in the present study

From Table 5 and Fig. 8 it can be seen that the maximum and minimum values observed for the volumetric heat of combustion, Q_v, for *Carpinus betulus* and *Populus nigra*, ranged from 16.06 to 7.04 kJ·cm^{-3}, respectively. A significant correlation between the Q_v and the D_0, was discovered (Fig. 8) by the R = 0.99. The relation $Q_v = f(D_0)$ can be described by the statistical formula (1):

$$Q_v = 20.135 \cdot D_0 - 69.255 \quad (\text{kJ·cm}^{-3}) \tag{1}$$

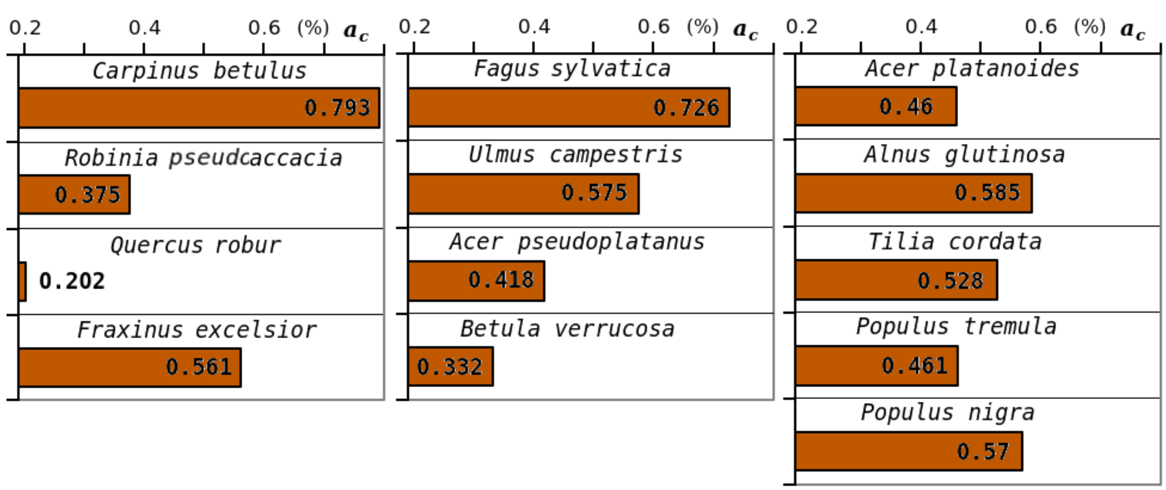

Fig. 9. Content of ash, a_c, in 13 wood specimens examined in the present study

Table 5 and Fig. 9 show that the observed ash content in the wood specimens, a_c, for *Carpinus betulus*, *Fraxinus excelsior*, *Acer pseudoplatanus*, and *Populus tremula* are greater than the values given in the literature (Wagenführ and Scheiber 1974).

For *Alnus glutinosa*, *Tilia cordata*, and *Populus nigra* the values for a_c, lie within the ranges given in the literature (Wagenführ and Scheiber 1974). For *Quercus robur*, *Ulmus campestris*, and *Betula verrucosa* values, the a_c is lower than the ranges given in previous studies (Wagenführ and Scheiber 1974). The maximum and minimum values of the a_c were observed for *Carpinus betulus* and *Quercus robur* specimens, ranging from

0.793% to 0.202%, respectively. It should be mentioned that the maximum difference observed in the a_c between values reported in the literature and the values reported in this study was 5.6% for the *Robinia pseudoacacia* specimens. Meanwhile, the minimum difference of 1.6% was observed for *Carpinus betulus* and *Fraxinus excelsior* specimens, by an average value of 3%. No correlation [R < abs(0.6)] (abs - absolute value), was found between Q_m and Q_v in the present study, as well as for the average content of cellulose c_c, lignin l_c, (R<0.3), and polysaccharides p_c, (R<0.45), reported in the literature (Wagenführ and Scheiber 1974). It has to be mentioned that in this literature, not all minimum and maximum values of the c_c, the l_c, and the p_c were reported. No correlation [R<*abs*(0.3)] was noticed between the ${}^{pK}Q_m$, evaluated in the present study (^{p}) and reported in the work of Krzysik (^{K}) (1975), and the average values of the ${}^{pW}a_c$, the ${}^{W}c_c$, the ${}^{W}l_c$, and the ${}^{W}p_c$, reported in the work Wagenführ and Scheiber (^{W}) (1974).

For the high and low density deciduous wood species examined in the present study, the actual amounts of main combustible substances (lignin, cellulose, and polysaccharides) were very random and did not follow values reported in the work of Wagenführ and Scheiber (1974). It should be noted that the amount of combustible substances that a tree can synthesize during growth seems to be more dependent upon growing conditions (soil, light, moisture, temperature, wind) than individual species characteristics. Figure 10 illustrates the presence of several elements: K, Ca, Mg, Na, Si, Al, Fe, Cu, Mn, S, and P in the ash that remained after burning. From this figure, it can be seen that in the ash of most wood specimens, the dominant element was Ca. Only in the case of wood of *Fraxinus excelsior* was the amount of Ca and K almost the same.

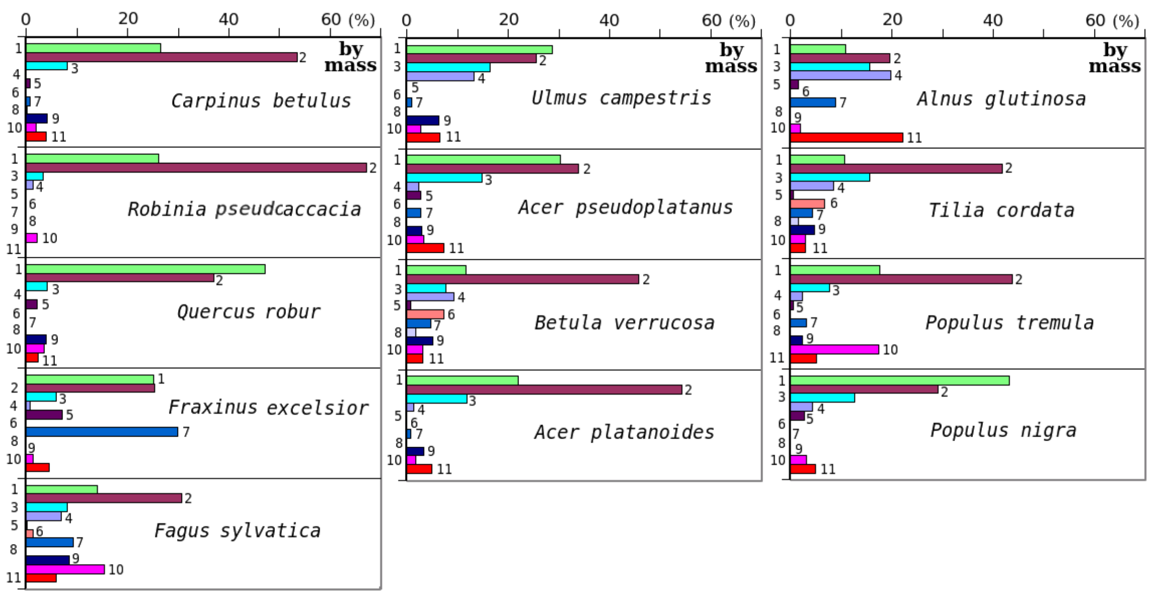

Fig. 10. EDAX average content of elements: 1 - K, 2 - Ca, 3 - Mg, 4 - Na, 5 - Si, 6 - Fe, 7 - Al, 8 - Cu, 9 - Mn, 10 - *S*, 11 - P in the ash from examined wood specimens

For *Quercus robur*, *Ulmus campestris*, and *Populus nigra*, the amount of K was larger than Ca. However, no reasonable correlation [R<abs(0.53)] was found between the Q_m, and the Q_v and the content of elements mentioned above. From Fig. 11 it can be seen that the coefficient of variation, c_v, for Al, Cu, Fe, Mg, P, S, and Si in ash particles was very large, which suggests a very random distribution in the wood structure.

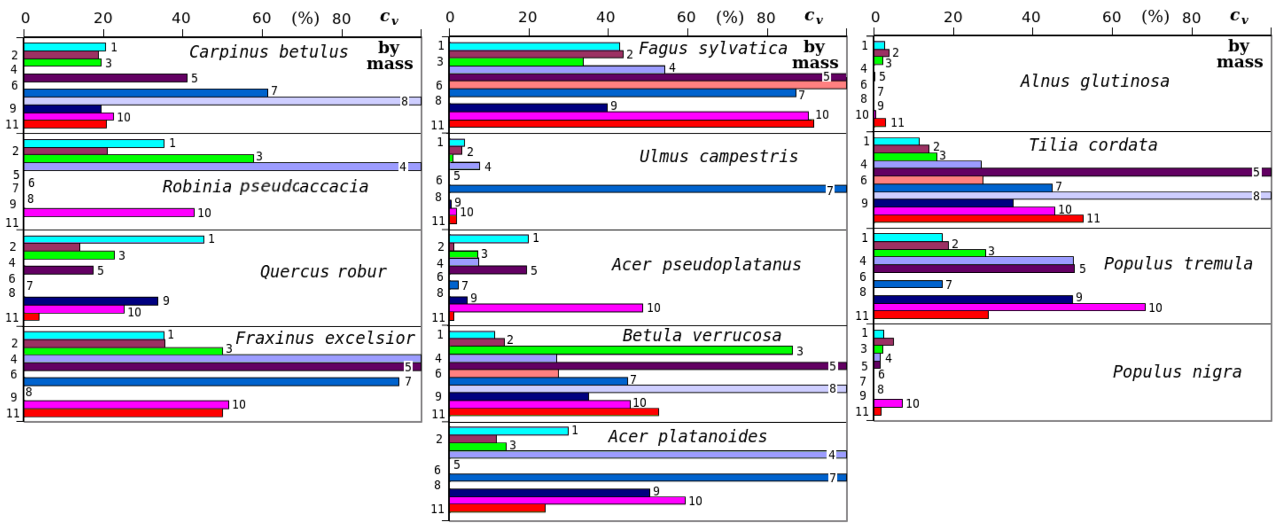

Fig. 11. Coefficients of variation, c_v, of EDAX content of elements: *1* - K, 2 - Ca, 3 - Mg, 4 - Na, 5 - Si, 6 - Fe, 7 - Al, 8 - Cu, 9 - Mn, 10 - S, 11 - P in ash from examined wood specimens

CONCLUSIONS

Experiments and analysis of results performed allow the researchers to state the following:

1. Between the volumetric heat of combustion, Q_v, and wood density, D_0, there is a significant correlation, calculated as $R = 0.99$.
2. The mass heat of combustion, Q_m, for *Acer platanoides* averaged 19.97 kJ·g^{-1}, which is nearly 1.6% larger than *Acer pseudoplatanus*.
3. During the examination of 13 deciduous wood species no correlation between mass heat of combustion, Q_m and wood density, D_0, was recognized.
4. The average mass heat of combustion Q_m, for all 13 examined wood specimens averaged 19.93 kJ·g^{-1} (S_d = 706 J·g^{-1}), which is 1.6% higher than value reported in the literature (Krzysik 1975).
5. No correlation was recognized between the mass heat of combustion Q_m, volumetric heat of combustion, Q_v, and the ash content in the wood, a_c, for the 13 deciduous wood species.
6. For the examined wood species, no correlation was found between the mass heat of combustion, Q_m, volumetric heat of combustion, Q_v, average content of cellulose, c_c, content of lignin, c_l, and the content of polysaccharides, c_p (Wagenführ and Scheiber 1974).
7. No correlation was recognized between the mass heat of combustion, Q_m, volumetric heat of combustion, Q_v, and the EDAX contents of K, Ca, Mg, Na, Si, Fe, Al, Cu, Mn, S, and P.

REFERENCES CITED

Ashby, M. F., and Jones, D. R. H. (1996). *Materiały Inżynierskie (Engineering Materials),* WNT, Warszawa, Poland.

Björn, G., Gebauer, K., Barkowski, R., Rosenthal, M., and Bues C. T. (2012). "Calorific value of selected wood species and wood products," *European Journal of Wood and Wood Products* 70(5), 755-757, DOI: 10.1007/s00107-012-0613-z.

Hubbe, M. (2008). "Are lignocellulosic resources too valuable to burn?" *BioResources* 3(2), 295-296. DOI: 10.15376/biores.3.2.295-296.

Instytut Technologii Drewna (Wood Technology Institute) http://www.itd.poznan.pl/pl/index.php?id=56, 19.11.2015.

Karaszkiewicz, A. (2008). "Ocena ciepła spalania i wartości opałowej wybranych sortymentów drewna robinii akacjowej na tle klas grubości (Heat of combustion and calorific value assessment of chosen sortiments of black locust for certain thickness classes)," *MOTROL* 10, 67-72.

Kienzle, E., Schrag, I., Butterwick, I., and Opitz, B. (2001). "Calculation of gross energy in pet foods: New data on heat combustion and fiber analysis in a selection of foods for dogs and cats," *J. Anim. Physiol. Anim.* 85(5-6), 148-157, DOI: 10.1046/j.1439-0396.2001.00311.x.

Krzysik, F. (1975). *Nauka o Drewnie (Wood Science)*, Państwowe Wydawnictwo Naukowe, Warszawa, Poland.

Wojciechowska, D. (1985). "Charakterystyka opałowa sortymentów leśnych i odpadów przemysłowych (Fuel characteristics of forest assortments and industrial waste)," *Prace Instytutu Technologii Drewna* 32(3/4), 4-22.

Wanin, S. (1949). *Drevesinovedenie (Wood Science)*, Goslesbumizdat, Moskva – Leningrad, Russia.

Wagenführ, R., and Scheiber, C. (1974). *Holzatlas*, VEB Fachbuchverlag, Leipzig, Germany.

White, R. H. (1987). "Effect of lignin content and extractives on higher heating value of wood," *Wood & Fiber Science* 18(4), 446-452.

Wood Handbook (1999). Tech. Report FPL-GTR 113, USDA Forest Service, Madison, WI (www.fpl.fs.fed.us./faqs.htm).

Article submitted: January 15, 2016; Peer review completed: March 4, 2016; Revised version received and accepted: March 15, 2016; Published: March 31, 2016.
DOI: 10.15376/biores.11.2.4402-4414