

Comparison of selected parameters of biomass and coal

*Justyna Lalak¹, Danuta Martyniak², Agnieszka Kasprzycka¹, Grzegorz Żurek², Wojciech Moroń³,
Mariola Chmielewska¹, Dariusz Wiącek¹, and Jerzy Tys¹*

¹Institute of Agrophysics, Polish Academy of Sciences, Doświadczalna 4, 20-290 Lublin, Poland

²Plant Breeding and Acclimatization Institute (IHAR) – National Research Institute, Radzików, 05-870 Błonie, Poland

³Institute of Heat Engineering and Fluid Mechanics, Wrocław University of Technology, Wybrzeże Wyspiańskiego 27, 50-370 Wrocław, Poland

Received February 15, 2016; accepted October 11, 2016

A b s t r a c t. As a fuel, biomass differs in its properties from fossil fuels and acquisition thereof for energy purposes is limited; hence, the ongoing search for new bioenergetically useful plants. The article presents the results of physical and chemical analyses of seven species of perennial grasses: tall wheatgrass, tall wheatgrass ‘Bamar’, brome grass, tall fescue ecotype, reed canary grass, giant miscanthus, and sorghum. The research involved technical and elemental analysis as well as analysis of the ash composition performed in order to determine their potential use for combustion process. The measurement results were compared with those obtained for hard coal and agricultural biomass, which is widely used in the energy industry. The results suggest that perennial grasses can successfully be combusted with similar performance to coal if burned in appropriate combustion installations.

K e y w o r d s: biomass, energy grass, combustion

INTRODUCTION

Increasing the proportion of renewable sources in the energy balance of Poland has become a necessity if the assessment criterion is based on the current prices of primary energy sources and the need for reduction of greenhouse gas emissions into the atmosphere. Fluctuations in prices of primary fuels (coal, oil, and gas) forces producers of electrical and thermal energy to search for new energy sources. In Poland and the European Union (EU), considerable emphasis is placed on renewable energy sources *ie* biofuels and solar, wind, and water energy (Nakomcic-Smaragdakis

et al., 2016). The development of technologies for acquisition of energy from renewable sources is regulated by legal solutions adopted in the EU, which aim at increasing the proportion of thermal and electrical energy produced from renewable sources. Analysis of the Polish energy sector reveals that it is primarily based on coal combustion. Therefore, one way of introducing renewable fuels in electricity production is biomass co-firing in conventional heat and electricity production systems. This allows simultaneous implementation of two guidelines *ie* increasing the use of renewable energy sources (RES) in the energy balance (McIlveen-Wright *et al.*, 2007).

Biomass as a one of the main resources can play a considerable role in a more diverse and sustainable energy mix. It can be used to reduce emissions related to the greenhouse effect, although it also decreases the need to import fossil fuels such as coal, oil, and natural gas, and finally it can provide an alternative source of income to local farmers, thereby strengthening the local economy (Arvelakis and Frandsen, 2010). Nevertheless, the conversion from fossil fuels towards biomass is demanding, and with new creativities, the know-how on the use of biomass has to be built up. The use of this new type of fuels in traditional coal-fired systems changes the firing conditions due to differences in both physical and chemical characteristics and can cause severe operational problems (Arvelakis and Frandsen, 2010; Nakomcic-Smaragdakis *et al.*, 2016).

Although there are multiple methods for thermochemical biomass utilisation, the most common forms include direct combustion and co-firing. These processes involve

*Corresponding author e-mail: j.lalak@ipan.lublin.pl

**This work was supported by the project: Biological Progress in Plant Production funded by the Ministry of Agriculture No. 83: ‘Production of energy forms of cultivated perennial grasses with increased biomass and calorific and seed value on dry, poor, and contaminated soils’, 2011-2013.

various types of solid biofuels, which can be divided into unprocessed (all types of branches, logs, woody plant parts, straw, *etc.* suitable for direct combustion), fragmented (wood shavings, sawdust, chaff, and other materials resulting from mechanical processing), and compressed (fuels in the form of *eg* pellets, briquettes, *etc.* produced under high pressure with or without binders). In each type, the physical properties relevant for implemented processes have to be assessed.

The major differences between biomass and coal include the higher moisture content of the raw biomass, which exerts an adverse effect on: the combustion efficiency and increases transport costs, higher volatile matter content, (which alters the ignition and combustion conditions), lower net calorific value of biomass, and a similar qualitative elemental composition accompanied by differences in the contents of elements. The physical and chemical properties of biomass are influenced by the term of biomass harvesting and genetically determined traits, which are to some extent modified by environmental conditions *eg* soil properties and fertilisation as well as precipitation rates.

The process of biomass combustion may be associated with certain risks that do not occur during combustion of coal. These include fuel pre-processing (fire-explosion risk), combustion *eg* including excessive slagging and ashing, and chlorine corrosion. Therefore, knowledge of the physicochemical properties of plant biomass helps to determine its potential application in heat or electricity production. The knowledge of these parameters allows proper selection of the amount of combusted biomass to ensure its minimal impact on the boiler system or the use of preventive measures minimising the negative impact of biomass combustion.

The aim of the study was to perform physico-chemical analysis of biomass from perennial grasses in terms of their suitability for use in energy processes.

MATERIAL AND METHODS

The research material comprised biomass from seven species of perennial grasses *ie* the tall wheatgrass (*Agropyron elongatum*): Nos 35-5f, 33-1f, and 35-8f, Bamar variety, the brome grass (*Bromus unioloides*) No. 3; the tall fescue (*Festuca arundinacea*) ecotype, the reed canary grass (*Phalaris arundinacea*), the giant miscanthus (*Miscanthus giganteus*), and the sorghum (*Sorghum*). Lignocellulosic biomass was collected in the generative phase from the experimental plots of IHAR in Radzików (Poland). The experiment was carried out in a random sub-blocks with 4 replications. The plant was harvested once a year since 2011. In order to obtain homogeneous samples, *ca.* 1 kg portions of each biomass type were dried and ground to a particle size < 0.2 mm. For comparative analysis, hard coal, pellets from *A. elongatum* 'Bamar' (Bamar pellets) and pellets from wheat straw were also examined.

The fragmented research material was subjected to physico-chemical analysis *ie* technical and elemental analysis, and the net calorific value (NCV) of the fuel was determined. Additionally, the ash composition was determined in the analysed biomass, including the content of silicon (Si), chlorine (Cl), and alkaline compounds (Al, Ca, Fe, Mg, P, K, Si, Na, Ti).

The technical (volatile matter and ash content) and transient moisture analysis followed the PN-EN ISO 18123:2016-01, PN-EN ISO 18122:2016-01, and PN-EN ISO 18134-2:2015 standards, respectively. The content of other combustible solid fractions *FC* (%) was determined from the difference (Eq. (1)):

$$FC = 100 - W - A - V, \quad (1)$$

where: *W* – moisture content (%), *A* – ash content (%), *V* – content of volatile matter (%).

The fuel ratio (*FR*, %) was calculated according to Eq. (2):

$$FR = FC/V. \quad (2)$$

In turn, the elemental analysis was carried out using an automated analyser Leco TruSpec CHNS in accordance with the PN-EN ISO 16948:2015-07E standard. Oxygen in the samples was determined using the indirect method specified in Eq. (3):

$$O = 100 - C - H - N - S - W - A, \quad (3)$$

where: *C*, *H*, *N*, *S*, *O* – content of elemental carbon, hydrogen, nitrogen, sulphur, and oxygen in the fuel (%)

The NCV was assessed using a calorimeter IKA C2000 in accordance with the PN-EN 15400:2011 standard. Calculation of the sample NCV expressed in kJ kg⁻¹ d.m. followed Eq. (4):

$$Q_i = Q - 24.42 (W + 8.94 H), \quad (4)$$

where: *Q_i* – net calorific value (condensed water vapour contained in exhaust gases), *Q* – gross calorific value (non-condensed water vapour contained in exhaust gases); 24.42 – heat of water evaporation in standard conditions per 1% (m m⁻¹) of water formed during the combustion or present in the analysed sample, 8.94 – coefficient of conversion of the hydrogen content into water, *W* – moisture content in the sample (%), and *H* – hydrogen content (%).

Determination of total chlorine was performed in accordance with the PN-EN ISO 16994:2015-06 standards using an Orion VERSA STAR apparatus equipped with an ion-selective module pH/ISE/temp with an ion-selective electrode 9617BNWP.

The chemical composition of ash in the analysed fuels was determined with a plasma spectrometer Thermo iCAP 6500 Duo ICP using ASCRM -010 as a standard (coal ash standard). The determination of the oxide composition (physico-chemical processes and phenomena) follows standards PN-EN ISO 16967:2016-06 (determination of major

elements: Al, Ca, Fe, Mg, P, K, Si, Na, and Ti) and PN-EN ISO 16968:2015-07 (determination of trace elements: As, Cd, Co, Cr, Cu, Hg, Mn, Mo, Ni, Pb, Sb, V, and Zn). The Cl content in ash was determined with the titration method in accordance with PN-EN 196-2:2013-11, and the content of carbonates in the form of CO₂ was assessed with a FTIR spectrophotometer.

Statistical analyses of collected data were performed using the statistical package STATISTICA (data analysis software system), Version. 10. Least significant differences (LSD) were determined from a 95% by Fisher test. Principal component analysis (PCA) was performed on average values for the different types of biomass, derived from technical analysis, elemental analysis of ash, with the exception of the chlorine content and CO₂. A rotation factor was conducted using the method of normalized varimax.

RESULTS AND DISCUSSION

The physical and chemical properties of hard coal and biomass are presented in Table 1. The analysed biomass types exhibited similar technical parameters, as evidenced by the 0.23÷0.28 range of the fuel ratio (*FR*). The low ratio suggests that the fuels were characterised by low content of

combustible solids (16÷19 % in the analytical condition) and high content of volatiles (60÷80% in the analytical condition), which is characteristic for the biomass.

The ash content in biomass fuels can vary from 1% weight basis in the case of wood to up to 15-20% in the case of some agricultural residues such as wheat straw, grape residues, and cotton gin residues (Arvelakis and Frandsen, 2010). However, in this study, the ash content of the biomass did not exceed 8.6% in the analytical conditions.

Shao *et al.* (2012a, 2012b) have found that biomass materials are commonly moist (17-25 wt% straw; 15-20 wt% reed canary grass (spring harvested)) and strongly hydrophilic as well as non-friable, which poses difficulties in fuel preparation, storage, and delivery. This can affect ash deposition during combustion. In this study, the moisture content (wt%) was between 2.9 and 8.8 wt%, which was significantly lower than in literature. Shao *et al.* (2010, 2011) conducted the first investigation of the effects of moisture content (<5 wt% and 30-35 wt%) in the feed on ash deposition during combustion of individual fuels (woody biomass/peat/coal) and some fuel blends. In their research, the as-received/air-dried feedstock that contained around 30 to 35% moisture performed better than the oven-dried feedstock in retarding ash deposition and chlorine deposition.

Table 1. Proximate and ultimate analyses of examined fuels (on air-dried basis)

Fuel	Proximate analyses					Ultimate analyses				
	<i>W</i>	<i>A</i>	<i>V</i>	<i>FC</i>	<i>Q_i</i>	<i>C</i>	<i>H</i>	<i>N</i>	<i>S</i>	<i>O</i>
	%				kJ kg ⁻¹ d.m.		%			
Hard coal	3.1	8.6	32.7	55.6	25741	75.7	4.3	1.2	1.2	5.9
Tall fescue ecotype	8.8	6.6	66.7	17.8	15981	45.4	5.6	0.7	0.1	32.8
Sorghum	7.9	7.2	67.6	17.3	15829	45.6	5.7	0.9	0	32.7
Reed canary grass	8.3	8.2	65.9	17.6	15933	44.9	5.8	0.9	0.1	31.9
Miscanthus	7.4	3.6	72.4	16.6	17185	48.4	6.0	0.4	0	34.2
Brome grass	8.2	4.4	68.6	18.7	16271	46.2	6.0	0.6	0	34.6
Tall wheatgrass 33 1f	6.2	8.5	66.9	18.5	15979	44.1	5.7	0.5	0	35.0
Tall wheatgrass 35 5f	7.5	5.9	68.2	18.5	16322	46.0	5.9	0.4	0	34.3
Tall wheatgrass 35 8f	6.7	5.9	68.7	18.6	16701	46.5	5.8	0.4	0	34.6
Tall wheatgrass Bamar	6.8	5.6	69.3	18.4	16489	46.0	5.9	0.5	0	35.2
Wheat straw pellet	2.9	5.8	74.8	16.6	18130	49.4	5.6	0.6	0.1	35.7
Pellet Bamar	6.9	6.4	68.8	17.9	17043	46.7	5.9	0.6	0	33.5
LSD (p > 95%)	0.116	0.247	0.482	0.521	107.314	0.289	0.094	0.032	0.013	0.461

W – moisture content in the analysed sample, *A* – ash content in the sample, *V* – volatile matter content, *FC* – combustible solid content, *Q_i* – net calorific value, d.m. – dry mass.

Comparison of the technical and elemental composition of the examined biofuels with coal shows differences between the fuels, including the characteristic nearly five-fold lower oxygen content in the coal *ie* the oxygen content did not exceed 10% by weight in the coal and amounted to *ca.* 30–40% by weight in the biomass. Another element is the substantially lower value of gross calorific value (GCV) in a range of 15–20 MJ kg⁻¹ d.m. in the case of biomass, which is similar to the GCV of brown coal, characterised by a lower degree of coalification than that of coal. There is also a large disproportion in the ratio of the combustible solid matter FC and volatile matter V.

The substantial proportion of volatile matter in the biomass fuel can be a positive factor in improvement of ignition of the dust-air cloud and flame stability; however, some volatile matter enhances the fire-explosion risk already in the pre-processing system. Such a ratio of volatile matter is suitable for application of biofuels in gasification and pyrolysis systems *ie* conversion of biomass (solid fuel) into syngas (gaseous fuel) used in gas turbines or as a secondary fuel in boiler systems. Another area of application based on the low energy density is the formation process *eg* palletisation yielding a secondary fuel with higher energy parameters suitable for use in combustion/co-firing processes.

The results of the determinations of the biomass NCV and GCV are presented in Table 2. The analysed types of biomass exhibited an average NCV of 16000 kJ kg⁻¹ d.m., which implies that these fuels can be used in such energy processes as combustion. Moreover it was observed that unprocessed biomass had lower NCV value than the biomass processed to form fuel pellets. In terms of coalification, such a high NCV ranks the fuels among moderate-quality brown coal.

Another important element determined in the analysis is the very low content of sulphur (below 0.1% in the analytical condition) and nitrogen (below 1.0% in the analytical condition) in the fuel; hence, these fuels can be used in combustion processes, yielding very low emissions of gas pollutants. This effect can be taken advantage of during co-firing with coal in large-scale industrial power plants, ensuring a measurable gain *ie* reduced NO_x and SO₂ emissions. Moreover, burning biomass fuels or biomass-coal mixtures containing low sulphur content is valuable for major reduction of SO_x/SO₂ emissions (Turn *et al.*, 2006) but might negatively influence the ash deposition behaviour, in particular Cl deposition. It has been generally accepted that the occurrence of S can alleviate corrosion problems associated with chloride deposits via the following sulphation mechanism (Shao *et al.*, 2012a).

In biomass, elements such as chlorine and potassium are mostly present as water soluble inorganic salts, and primarily as chloride, nitrates, and oxides *etc.* which can be easily volatilized during the combustion, resulting in high mobility for alkali materials and, consequently, high pollution tendency (Shao *et al.*, 2012a).

An important element in the use of biofuels in the power industry, in particular in the combustion process, is their adverse effect on the slagging and fouling processes. The chemical composition of biomass ash is significantly different from that of coal (Shao *et al.*, 2012a). The mineral material from biomass does not contain aluminosilicates, but does contain quartz and simple inorganic salts of potassium, calcium, magnesium, and sodium in the form of phosphates, sulphates, and chlorides. The chemical composition of ashes is shown in Table 3. The analysed ashes differed in the content of the major elements from those derived from incineration of coal. Noteworthy, there was a considerable variation in the oxide composition in the

Table 2. Net calorific value (Q_i , kJ kg⁻¹ d.m.) and gross calorific value of analysed biomass (Q , kJ kg⁻¹ d.m.)

Component	Condition	Tall fescue ecotype	Sorghum	Reed canary grass	Miscanthus	Brome grass	Tall wheatgrass 33 1f	Tall wheatgrass 35 5f	Tall wheatgrass 35 8f	Tall wheatgrass Bamar	Pellet Bamar	LSD (p>95%)
	Analytical	15981	15829	15933	17185	16271	15979	16322	16701	16489	17043	107.345
Q_i	Dry	17526	17181	17379	18549	17731	17027	17640	17906	17692	18306	105.234
	Dry ash-free	18898	18646	19078	19302	18629	18722	18837	19113	18816	19659	103.841
	Analytical	14546	14402	14467	15691	14757	14583	14849	15261	15030	15587	107.314
Q	Dry	16189	15841	16002	17130	16300	15700	16245	16538	16306	16924	103.271
	Dry ash-free	17457	17191	17566	17826	17126	17262	17348	17653	17341	18174	106.342

Table 3. Chemical composition of ashes (%)

Component	Hard coal	Tall fescue ecotype	Sorghum	Reed canary grass	Miscanthus	Brome grass	Tall wheatgrass 33 1f	Tall wheatgrass 35 5f	Tall wheatgrass 35 8f	Tall wheatgrass Bamar	Wheat straw pellet	Pellet Bamar	LSD (p>95%)
SiO ₂	40.6	54.3	53	61.6	43.8	42.8	53.1	59.1	59.6	61.7	60	63.2	0.675
Fe ₂ O ₃	10.7	0.1	0.18	0.05	0.24	0.08	0.11	0.19	0.11	0.11	0.92	0.88	0.078
Al ₂ O ₃	26.9	0.18	0.23	0.05	0.52	0.1	0.2	0.26	0.23	0.23	1.58	1.74	0.116
Mn ₃ O ₄	0.04	0.08	0.1	0.07	0.46	0.07	0.02	0.02	0.03	0.07	0.22	0.09	0.024
TiO ₂	0.91	0.01	0.02	<0.01	0.03	0.01	0.01	0.02	0.01	0.01	1.25	0.15	0.033
CaO	4.81	3.79	8.1	2.84	7.45	5.45	2.85	3.22	2.91	3.29	9.46	4.7	0.124
MgO	2.32	2.6	2.42	1.72	2.54	1.4	0.62	0.83	0.66	0.74	1.86	1.37	0.076
SO ₃	4.64	2.29	2.25	1.91	1.76	1.07	1.92	1.29	1.12	1.07	2.44	1.36	0.045
P ₂ O ₅	0.71	5.86	8.53	6.58	5.59	9.83	6.44	5.78	6.05	6.67	2.36	4.66	0.056
Na ₂ O	6.15	0.15	0.2	0.23	0.24	0.34	0.11	0.28	0.27	0.19	0.86	0.86	0.052
K ₂ O	1.92	25.1	20.6	19.6	26.5	30.2	27.5	24.1	23.8	21.3	14.6	17.5	0.428
BaO	0.1	0.01	0.01	0.01	0.04	<0.01	0.01	0.01	0.01	0.02	0.07	0.03	0.013
SrO	0.08	0.01	0.04	0.01	0.02	0.02	0.01	0.01	0.01	0.01	0.03	0.02	0.016
Cl	<0.1*	3.09	1.25	4	2.7	6.23	5.7	3.24	3.66	3.27	1.13	1.81	0.098
CO ₂	–	1.56	2.1	0.48	7.43	1.52	0.82	0.72	0.86	0.6	2.25	0.76	0.064
Sum	99.88	99.13	99.03	99.15	99.32	99.12	99.42	99.07	99.33	99.28	99.03	99.13	LSD (p>95%)

*According to Shao *et al.* (2011; 2012a).

ashes from the different biofuels and coal. A characteristic feature of the biomass ash is the high content of phosphorus and potassium compounds, with the highest value noted in the brome grass sample. The highest total potassium and sodium content was reported in the case of the brome grass, the tall wheatgrass 33 1f, and the miscanthus. The ‘Bamar’ pellet exhibited the highest sodium content of all the samples analysed. The silica content was in the range of 43–63%, potassium 17–30%, and chlorine 1.2–6.2% according to Veijonen *et al.* (2000), Arvelakis *et al.* (2001), Armesto *et al.* (2003), Aho *et al.* (2004), and Shao *et al.* (2012b). Interestingly, considerable contents of calcium, magnesium, phosphorus, and potassium were noted in the ashes yielded by biomass combustion. Biomass ash is thus characterised by a low melting temperature and a high tendency to slagging and fouling. Ca and Mg compounds

usually increase the ash melting temperature, while K and Na reduce it. In combination with potassium, silicon can induce formation of low-melting silicates in volatile ash particles. These processes are highly important, given the risk of fouling and ash slagging on the walls of furnaces or heated surfaces. The main effect of biomass co-firing with coal is the emission of vapours of potassium compounds and subsequent condensation on the surface of ash particles and boiler pipes (Rosendahl, 2013; Shao *et al.*, 2012a).

Increased levels of sodium and potassium compounds in biomass are a highly unfavourable phenomenon due to the process of slagging and ashing. These components are characterised by formation of low-melting eutectics, which contribute to a faster rate of ash melting and deposition on superheater tubes and heating surfaces. Experimental results (Cardozo *et al.*, 2014; Nowak-Woźny *et al.*, 2011,

Table 4. Chlorine content in biomass

Fuel	Chlorine content % (d.m.)
Tall fescue ecotype	0.31
Sorghum	0.10
Reed canary grass	0.35
Miscanthus	0.10
Brome grass	0.42
Tall wheatgrass 33 1f	0.39
Tall wheatgrass 35 5f	0.25
Tall wheatgrass 35 8f	0.28
Tall wheatgrass Bamar	0.27
Pellet Bamar	0.26
LSD (p>95%)	0.083

2013) prove that addition of even a small amount of biomass to coal combustion can significantly increase the risk of fouling and slagging of the coal-biomass mixture. The differences in the chemical composition of ash biomass could be caused by agricultural operations. A plausible hypothesis is that on-field shredding with the forage harvester produced a loss of biomass material such as leaves, which are known to contain higher nutrient amounts (Fournela *et al.*, 2015; Prohnow *et al.*, 2009).

Theis *et al.* (2006) conducted a comparison of the straw, peat, and bark ash deposition behaviours with different chemical compositions. They concluded that straw had higher fouling tendency than peat and bark, due to the large amounts of water-soluble compounds occurring in the straw. Moreover, Baxter (2005) found that the highly active alkali/alkaline metals (for instance K, Na, Ca) and Cl contents could simply form vapour phase chloride compounds/ions. Due to the low melting points (<800°C), these chloride compounds (*eg* KCl) could deposit and form a sticky layer on the heat transfer surfaces or heat exchanger (Shao *et al.*, 2012a). Consequently, more inorganic particles in fly ash will have a high predisposition of adhering to the particles in the existing layer, leading to the ash layer growth (Nielsen *et al.*, 2000; Shao *et al.*, 2012a). Furthermore, some kinds of biomass fuels contain significant amounts of silica, for instance the silica content in rice straw is usually at 10 wt% of dry biomass weight. Silicates associated with alkaline/alkaline metals could sinter at 800-900°C or melt, which can occur during the solid phase or more frequently the vapour phase, *via* fly ash throughout combustion processes (Shao *et al.*, 2012a). The produced alkali silicates and mixed alkali and/or calcium chlorides/sulphates have a tendency to deposit on heat exchanger surfaces or reactor walls, leading to fouling/corrosion even at a low fusion temperature (<700°C) (Arvelakis *et al.*, 2005; Shao *et al.*, 2012a).

Another important element observed during the biomass combustion process is the occurrence of corrosion. Therefore, determination of the chlorine content in the analysed material was carried out in the subsequent stage of the investigations. The chlorine content in the analysed types of

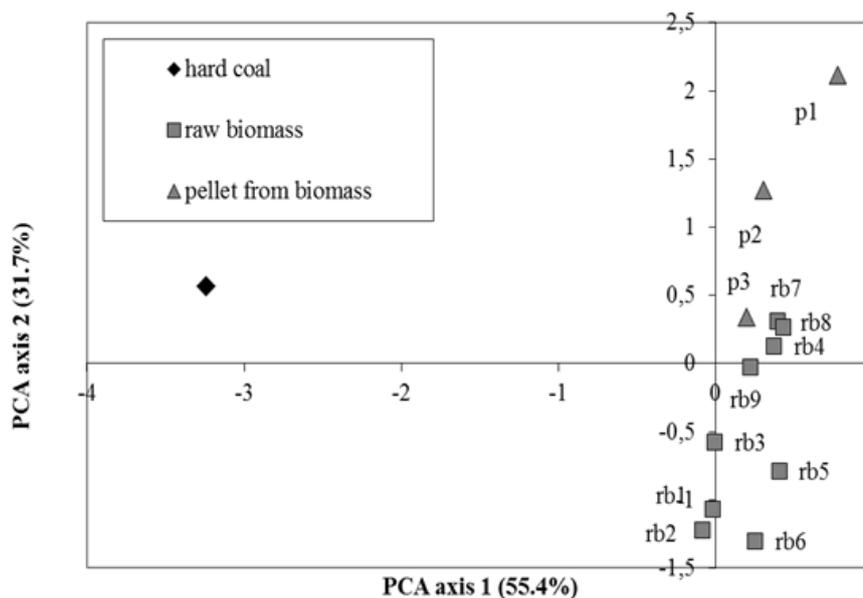


Fig. 1. PCA analysis of average values for different types of biomass, derived from technical analysis and elemental analysis of ash. p1 – pellet from wood, p2 – pellet from wheat straw, p3 – pellet from *A. elongatum* ‘Bamar’, rb1 tall fescue, rb2 – sorghum, rb4 – Phalaris, rb4 – Tall wheatgrass 35/5, rb5 – Miscanthus, rb6 – Brome grass, rb7 – tall wheatgrass 35/1, rb8 – tall wheatgrass ‘Bamar’, rb9 – tall wheatgrass 33.

biomass was in the range of 0.10-0.42% (Table 4), which is in agreement with the studies of Shao *et al.* (2012a, 2012b) who compared the chlorine content of six sorts of feedstock – woody biomass, bark, straw, willow, reed canary grass, peat with other fuels for power/heat generation. The highest chlorine content was detected in the brome grass sample (0.42%) and the lowest in the sorghum and miscanthus samples (0.10%). However, in straw and energy crops, high chlorine (Cl) concentrations are very common (Shao *et al.*, 2012a). Chlorine is an undesirable element in the process of fuel combustion due to the increased risk of high-temperature chlorine corrosion. The enhanced risk of corrosion is associated with the chemistry of ash deposits accumulated on boiler surfaces. The surfaces of superheaters are mostly at risk due to the high temperature of the operating factor, which results in increased tendency of surface deposits to melt and react with the surface of superheater tubes. Changes in the ash composition and quality occurring during the co-firing process may also influence the use and storability of ashes. The methods applied in energy industry for purifying solid-derived exhausts in electrostatic precipitators or wet desulphurisation lead to formation of by-products, which are used in other sectors, *ie* construction and cement industries. An increase in the amounts of undesirable substances may result in difficulties in management thereof and a necessity to store them, which significantly reduces the efficiency of power plants.

For the information about the mutual similarity between studied biomass and coal, the main factor analysis (PCA) has been carried out. The experimental data were subjected to a PCA where the first two principal components (PCs) explained 87.1% of the variance. The first principal components (55.4% variation) were correlated with the parameters of the technical and elemental analysis (except A and W), while the second principal components (31.7% variation) were correlated with W and a number of parameters describing the chemistry of ash (TiO_2 , P_2O_5 , K_2O and BaO). Projection of the studied fuels in the first and second principal components (Fig. 1.) indicates a remarkable distinction of coal, as well as a distinct difference between the raw biomass (grass) and biomass processed to form fuel pellets. The distinctiveness of coal was mainly determined by the variables correlated with the first factor, while the differentiation of other fuels depends mainly on the value correlated with the second factor. The relative positions of the respective points on the figure indicate similarity of biomass from one species – wheatgrass and relatively better performance of the biomass (higher y-axis) compared to the others.

CONCLUSIONS

1. The analysed fuels were characterised by similar technical parameters. The biomass exhibited high content of volatile matter (over 60%) and content large amount of

ash (below 10%). Such properties of fuels are suitable for application thereof in the gasification/pyrolysis processes. The elemental analysis of the investigated fuels has shown very low contents of sulphur and nitrogen, which might contribute to reduction of emissions of gaseous NO_x and SO_2 pollutants when the fuels are used for energy purposes.

2. The average net calorific value of the analysed fuels was at a level of $16 \text{ MJ kg}^{-1} \text{ d.m.}$, which can ensure energy application thereof in the combustion and co-firing processes, and the value qualifies the fuels as a valuable energy source

3. The content of chlorine in the examined fuels was in a range of 0.1-0.4% and it exceeds the content detected in fossil fuels. This undesirable factor can increase the risk of low- and high-temperature corrosion; however, the severity of these phenomena is a resultant of many factors, including the ash oxide composition or the organisation of the combustion process.

4. The analysed types of biomass were characterised by a higher proportion of potassium compounds and a lower proportion of sodium compounds, than in coal, which promote formation of low-melting eutectics. The risk of slagging and fouling of heating surfaces is difficult to eliminate from the combustion process; yet the low ash content in biomass reduces the risk, but the biomass composition is highly unfavourable. Co-firing with coal or application of additives binding undesirable components are potential methods for minimisation of the slagging and fouling occurrence.

5. Due to the high content of acidic components, especially of silica, the biomass of perennial grasses (tall wheatgrass Bamar, reed canary grass) is a raw material with the most favorable parameters for energy use.

Conflict of interest: Authors not declare conflict of interest.

REFERENCES

- Aho M. and Silvennoinen J., 2004. Preventing chlorine deposition on heat transfer surfaces with aluminium-silicon rich biomass residue and additive. *Fuel*, 83, 1299-1305.
- Armesto L., Bahillo A., Cabanillas A., Veijonen K., Otero J., Plumed A., and Salvador L., 2003. Co-combustion of coal and olive oil industry residues in fluidized bed. *Fuel*, 82, 993-1000.
- Arvelakis S. and Frandsen F.J., 2010. Rheology of fly ashes from coal and biomass co-combustion. *Fuel*, 89, 3132-3140.
- Arvelakis S., Gehrman H., Beckmann M., and Koukios E.G., 2005. Preliminary results on the ash behaviour of peach stones during fluidized bed gasification: Evaluation of fractionation and leaching as pre-treatments. *Biomass Bioenergy*, 28, 331-338.
- Arvelakis S., Vourliotis P., Kakaras E., and Koukios E.G., 2001. Effect of leaching on the ash behavior of wheat straw and olive residue during fluidized bed combustion. *Biomass Bioenergy*, 20, 459-470.

- Baxter L., 2005.** Biomass-coal co-combustion. Opportunity for affordable renewable energy. *Fuel*, 84, 1295-1302.
- Cardozo E., Erlich C., Alejo L., and Fransson T.H., 2014.** Combustion of agricultural residues: an experimental study for small-scale applications. *Fuel*, 115, 778-787.
- Fournela S., Palaciosb J.H., Morissettec R., Villeneuvec J., Godboutb S., Heitza M., and Savoiec P., 2015.** Particulate concentrations during on-farm combustion of energy crops of different shapes and harvest seasons. *Atmospheric Environment*, 104, 50-58.
- McIlveen-Wright D.R., Huang Y., Rezvani S., and Wang Y., 2007.** A technical and environmental analysis of co-combustion of coal and biomass in fluidised bed technologies. *Fuel*, 86, 2032-2042.
- Nakomcic-Smaragdakis B., Cepic Z., and Dragutinovic N., 2016.** Analysis of solid biomass energy potential in Autonomous Province of Vojvodina. *Renewable and Sustainable Energy Reviews*, 57, 186-191.
- Nielsen H.P., Baxter L.L., Sclippab G., Morey C., Frandsen F.J., and Dam-Johansen K., 2000.** Deposition of potassium salts on heat transfer surfaces in straw-fired boilers: A pilot-scale study. *Fuel*, 79, 131-139.
- Nowak-Woźny D., Moroń W., Hrycaj G., and Rybak W., 2011.** The changes of electrical properties and phase equilibrium state during sintering of the biomass the sewage sludge and the coal ashes. *European Combustion Meeting, ECM*, June 28-July 1, Cardiff, Wales.
- Nowak-Woźny D., Moroń W., Hrycaj G., and Rybak W., 2013.** Electrical properties of the sintered biomass, sewage sludge and coal ash. *Przegląd Elektrotechniczny*, 89, 2a, 75-77.
- PN-EN 15400:2011. Solid fuels – Determination of lower heating value.
- PN-EN 196-2:2013-11. Methods of testing cement. Part 2: Chemical analysis of cement.
- PN-EN ISO 16948:2015-07E. Solid fuels - Determination of carbon, hydrogen and nitrogen by automatic analyzer - macro method.
- PN-EN ISO 16967:2015-06. Solid biofuels – Determination of major elements - Al, Ca, Fe, Mg, P, K, Si, Na and Ti.
- PN-EN ISO 16968:2015-07. Solid biofuels – Determination of minor elements – As, Cd, Co, Cr, Cu, Hg, Mn, Mo, Ni, Pb, Sb, V and Zn.
- PN-EN ISO 16994:2015-06. Solid biofuels – Determination of total sulfur and chlorine.
- PN-EN ISO 18122:2016-01. Solid fuels – Determination of ash content by gravimetric method.
- PN-EN ISO 18123:2016-01. Solid fuels – Determination of volatile content by gravimetric method.
- PN-EN ISO 18134-2:2015. Solid fuels – Determination of moisture content.
- Prohnow A., Heiermann M., Plöchl M., Amon T., and Hobbs P.J., 2009.** Bioenergy from permanent grassland - a review: 2. Combustion. *Bioresour. Technol.*, 100, 4945-4954.
- Rosendahl L., 2013.** Biomass Combustion Science, Technology and Engineering. Woodhead Publishing, Denmark.
- Shao Y., Wang J., Preto F., Zhu J., and Xu C., 2012a.** Ash deposition in biomass combustion or co-firing for power/heat generation. *Energies*, 5, 5171-5189.
- Shao Y., Xu C.C., Zhu J., Preto F., Wang J., Tourigny G., Badour C., and Li H., 2012b.** Ash and chlorine deposition during co-combustion of lignite and a chlorine-rich Canadian peat in a fluidized bed-effects of blending ratio, moisture content and sulfur addition. *Fuel*, 95, 25-34.
- Shao Y., Xu C.C., Zhu J., Preto F., Wang J., Li H., and Badour C., 2011.** Ash deposition in co-firing three-fuel blends consisting of woody biomass, peat, and lignite in a pilot-scale fluidized-bed reactor. *Energy Fuels*, 25, 2841-2849.
- Shao Y., Xu C.C., Zhu J., Preto F., Wang J., Tourigny G., Badour C., and Li H., 2010.** Ash deposition during co-firing biomass and coal in a fluidized-bed combustor. *Energy Fuels*, 24, 4681-4688.
- Theis M., Skrifvars B.-J., Zevenhoven M., Hupa M., and Tran H., 2006.** Fouling tendency of ash resulting from burning mixtures of biofuels. Part 2: Deposit chemistry. *Fuel*, 85, 1992-2011.
- Turn S.Q., Jenkins B.M., Jakeway L.A., Blevins L.G., Williams R.B., Rubenstein G., and Kinoshita C.M., 2006.** Test results from sugar cane bagasse and high fiber cane co-fired with fossil fuels. *Biomass Bioenergy*, 30, 565-574.
- Veijonen K., Vainikka P., Järvinen T., and Alakangas E., 2000.** Processes, V. Biomass Co-Firing: An Efficient Way to Reduce Greenhouse Gas Emissions; European Bioenergy Networks: Espoo, Finland.