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ASSESSMENT OF QUALITY AND ENERGY OF SOLID BIOFUEL PRODUCTION

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Abstract

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The work presents an assessment of the quality and specific energy of solid biofuels from selected plant materials. Their production used wheat straw, rye straw, maize straw, rape straw, and meadow hay. The plant materials were ground with a stationary barrel grinder at the theoretical cutting length of 20 mm prior to briquetting, and with a hammer grinder equipped with riddles with a hole which diameter is of 8 mm prior to form into pellets. The moisture of the compacted raw materials was determined by the scale-dryer method, and their calorific value was determined with the KL-12Mn calorimeter. The agglomeration of the plant materials involved a pellet press with a fixed single-sided flat matrix powered by compacting rolls, and a spiral briquette press with a heated compacting chamber. The conducted research covered the measurements of the mechanical durability and specific energy in the agglomeration of the applied plant materials. The obtained results of the tests of the quality and specific energy of biofuel production were subject to statistical analysis.

Key words: solid biofuel, mechanical durability, specific energy

Introduction

The issues of environment protection associated with the exploitation and depletion of fossil-fuel reserves and the emission of pollution contribute to the growing use of renewable-energy sources. In the current situation of energy production from conventional fuels, there is more and more attention being paid to the issues associated with the protection of the natural environment. This results from the rising ecological awareness of communities and the desire to counter the greenhouse effect and global warming. A considerable reduction in emitted substances considered as harmful to the environment can be achieved with the use of biomass for energy purposes (Wisz and Matwiejew, 2005). However, the production of energy from biomass should not entail any damage resulting from the acquisition of adequate food resources and fodder.

A favourable occurrence associated with the acquisition of biomass for energy purposes is the limitation of carbon dioxide emissions. The CO_2 stream emitted during the biomass-combustion process is absorbed during the photosynthesis process and is used to grow plants in the vegetation process. This is associated with the reduction of the negative impact on the natural environment resulting from the use of fossil fuels (the emission of harmful pollution, the creation of waste, soil and landscape degradation). Plant biomass is constantly regenerated and its utilisation provides an opportunity to increase the income of e.g. agriculture, the farming and food production industry, and forestry management. There is also an opportunity to create new jobs for people working in the production of biomass and the devices to process it, as well as biofuels for the energy and heating sector.

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Plant-based biomass holds great energy potential. It covers the waste from agricultural production (e.g. straw, hay), forestry production (felling, bark), and the woodwork industry (sawdust, shavings). A large group in the biomass structure is composed of raw materials originating from one-year and multiyear agricultural cultivation, which includes fast-growing trees and bushes (poplar, willow), perennials and grasses (*Jerusalem artichoke*, *Virginia fanpetals*, *Miscanthus giganteus*), and other plants (Majtkowski, 2007; Stolarski et al., 2008). Due to their low density and calorific value (with reference to unit volume), these raw materials are difficult to distribute and use in their unprocessed form. In order to improve their usefulness for energy purposes, their density must be increased; this occurs through the pressure compacting of the raw materials ground during the forming into pellets or briquetting processes (Garcia-Maraver et al., 2011; Mani et al., 2006; Obernberger and Gerold, 2004).

In structure of renewable resources leading position in Poland has biomass (Janowicz, 2006). Currently biomass is obtained from forestry production, wood-processing plants, and maintenance of municipal green areas and in small amounts of organic fraction of segregated municipal wastes (Szyszlak-Bargłowicz et al., 2012). Plant biomass, particularly the straw of cereals and other arable plants in their original form, takes up a great deal of transport and storage space and has a low calorific value under the unit volume. In this situation, it should be adequately processed in order to improve its energy effectiveness. This entails the pursuance of the agglomeration of plant-based raw materials through their briquetting or form into pellets. This increases the concentration of the mass and energy in the unit volume of such biofuels and considerably improves their distribution and utilisation (Thek and Obernberger, 2012).

In recent years, physical properties have been studied for various crops and agricultural materials. Information on physical properties of plant biomass is necessary to design equipment for grading, processing and storage (Karababa, 2006; Carroll and Finnan, 2012; Wu et al., 2011). The last few years have observed a significant growth and development of applying biomass waste for energy purposes in the form solid fuel. One of the methods of converting biomass (including plant biomass) into energy is producing solid fuels in the form of pellets or briquettes through pressure agglomeration (Carone et al., 2011; Nilsson et al., 2011).

The objective of the work was to assess the quality and specific energy of pellet and briquette production from selected plant materials.

Materials and Methods

For the pellet and briquette production used wheat straw, rye straw, maize straw, rape straw, and meadow hay. The plant materials were ground with a stationary barrel grinder at the theoretical cutting length of 20 mm prior to briquetting. Next, they were additionally ground with a hammer grinder equipped with riddles with a hole, which diameter is of 8 mm, prior to form into pellets. The relative moisture of the plant materials was determined with the scale-dryer method in compliance with the PN-EN 15414-3:2011 standard, while their calorific value was determined with a KL-12Mn calorimeter with the PN-EN 14918:2010 standard. The agglomeration of the plant materials applied a pellet press with a fixed single-sided flat matrix and powered compacting rolls with an electrical 7.5 kW motor and a spiral briquette press with a heated compacting chamber. The agglomerating spiral of the briquette press was powered by a 4.5 kW motor, while the compacting chamber was heated with electrical 3 kW heaters. The temperature value of produced pellets was measured with the use of a ST-8869 pyrometer.

The conducted research covered the measurements of the mechanical durability and specific energy in the agglomeration of the applied plant materials. The measurements of the mechanical durability of the pellets and briquettes were conducted at a testing station in compliance with the current standards, i.e.: PN-EN 15210-1: 2010 and PN-EN 15210-2: 2011. The tests performed in five attempts served to determine the mechanical durability of the produced solid biofuels for the tested plant materials in compliance with the following equation (1):

$$D_U = \frac{m_A}{m_E} .100 \ (\%), \tag{1}$$

where D_U – mechanical durability (%),
m_A – mass of agglomerates after durability test (g),
m_E – mass of agglomerates before durability test (g).

The volume of the energy expenditures was established with the use of a Lumel 3000 power, time, and electrical energy converter connected to a computer. This converter registered the consumption of temporary power and the energy consumption of the neutral gear of the device and the compacting process, as well as the duration of the compacting process. The specific energy measurements were conducted after the achievement of the expected temperature in the compacting chamber of the briquette press. The results of the electrical-energy consumption were converted into a mass unit of produced pellets or briquettes.

The obtained results of the tests of mechanical durability and specific energy of solid biofuel production were subjected to a statistical analysis on the STATISTICA 6.0 software, based on the analysis of the variances and the Tukey test. The statistical analyses assumed a level of significance of α = 0.05.

Test Results

Table 1 contains the specification of the agglomerated plant materials. The average moisture of the dry raw materials was between 12.3% for rape straw and 14.1% for maize straw. Meanwhile, the average calorific value was between 16.6 MJ kg^{-1} for meadow hay and 17.5 MJ kg^{-1} for maize straw. The temperature of produced pellets from used plant materials, after leaving the matrix of forming into pellets machine, amounted to an average of 80°C ± 5°C.

Table 1

The physical properties of the agglomerated plant materials

Type of plant materials	Moisture of the dry state, %	Calorific value of the dry state, MJ kg^{-1}
Wheat straw	13.2	16.8
Rye straw	12.8	17.1
Maize straw	14.1	17.5
Rape straw	12.3	17.3
Meadow hay	13.5	16.6

Table 2

One-way analysis of variance table for mechanical durability

Source of Variability	df	SS	MS	F	p
Plant material	3	588.8	196.3	10.63	0.000215
Error	20	369.2	18.5		

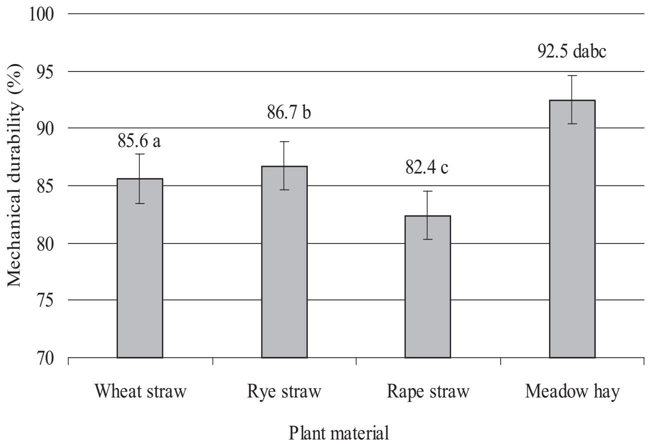

Fig. 1. Effect of kind the plant materials on mechanical durability

The analysis of the variances showed that the plant materials used in the tests affect the mechanical durability of the pellets (Table 2). There were statistically-significant differences established in the mechanical durability of pellets made from wheat straw, rye straw and rape straw. While there were not stated statistically-significant differences between these pellets, and the pellets made from meadow hay (Figure 1).

The lowest mechanical durability was noted in pellets made of rape straw (82.4%), while the meadow hay pellets had the highest value (92.5%). In relation to the durability of the pellets made from rape straw, the mechanical durability was higher by 3.2 percent point for wheat-straw pellets, by 4.3 percent point for rye-straw pellets, and by 10.1 percent point for meadow-hay pellets.

The conducted analysis of the variances showed that the plant materials used in the tests also affect the consumption of the energy used during the forming into pellets process (Table 3). There were statistically-significant differences established in the specific energy of pellets made from wheat straw, rye straw and rape straw. While there were not stated statistically significant differences between these pellets, and the pellets made from meadow hay (Figure 2).

Table 3

One-way analysis of variance table for specific energy

Source of Variability	df	SS	MS	F	p
Plant material	3	0.0151	0.005	11.75	0.00011
Error	20	0.0086	0.004		

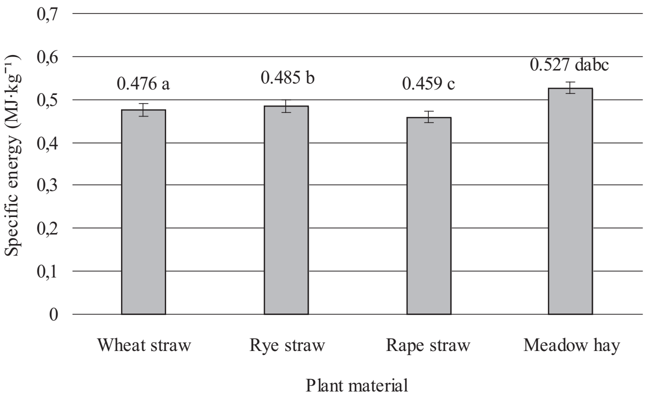

Fig. 2. Effect of kind the plant materials on specific energy

The lowest specific energy was noted in pellets made of rape straw (0.46 MJ kg^{-1}), while the meadow-hay pellets had the highest value (0.53 MJ kg^{-1}). In relation to the specific energy of the pellets made from rape straw, the specific energy growth was higher by approximately 5% for wheat-straw and rye-straw pellets, and by approximately 15% for meadow-hay pellets.

The analysis of variance showed that both the tested plant materials and the temperatures set in the compacting chamber of the briquette press have significant impact on the mechanical durability of the briquettes and the consumption of energy in their production. Statistically-significant differences were noted in both the mechanical durability and specific energy of all agglomerated plant materials (Tables 4 and 5).

Table 4

Two-way analysis of variance table for mechanical durability

Source of Variability	df	SS	MS	F	p
Plant material (P)	3	1804.7	601.6	56.79	0.000000
Temperature (T)	2	7877.5	3938.7	371.80	0.000000
(P) x (T)	6	40.2	6.7	0.63	0.703458
Error	60	635.6	10.6		

Table 5

Two-way analysis of variance table for specific energy

Source of Variability	df	SS	MS	F	p
Plant material (P)	3	0.16775	0.05592	69.03	0.000000
Temperature (T)	2	0.08132	0.04066	50.20	0.000000
(P) x (T)	6	0.00161	0.00027	0.33	0.918427
Error	60	0.04860	0.00081		

Figure 3 presents the measurement results of the mechanical durability of briquettes depending on the temperature of the compacting chamber of the briquette press and the used plant materials. The increase in the temperature in the compacting chamber was accompanied by a growth in the mechanical durability of the briquettes. The rape-straw briquettes had the lowest mechanical durability (58.2 - 81.4%), while the maize-straw briquettes had the highest value (70.5 - 95.5%). The rise in the temperature from 200 to 250ºC

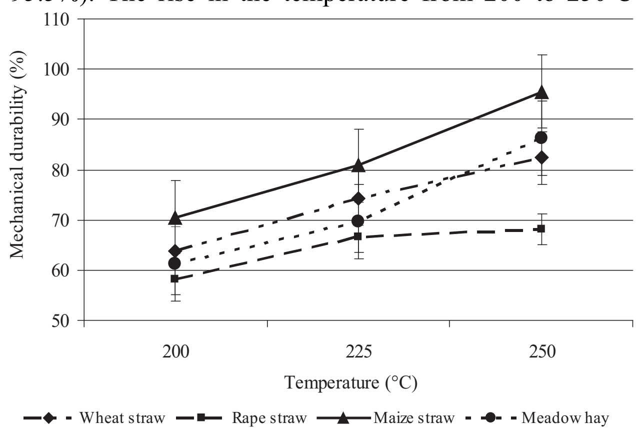

Fig. 3. Effect of temperature on mechanical durability

caused the mechanical durability of the briquettes to rise on average by 23% for rape straw, and 28% for wheat straw.

Figure 4 presents the measurement results of the electrical-energy-consumption briquettes, depending on the temperature of the compacting chamber of the briquette press and the plant materials used in the briquetting process. The rise in the temperature in the compacting chamber was accompanied by a reduction in electrical-energy consumption. The lowest values of specific energy were noted in the production of wheat-straw briquettes (0.39–0.45 MJ kg^{-1}), while the maize-straw briquettes had the highest value (0.50–0.59 MJ kg^{-1}). The rise in the temperature in the compacting chamber of the briquette press from 200 to 250°C caused electrical-energy consumption to drop by 17–19% for all the produced briquettes.

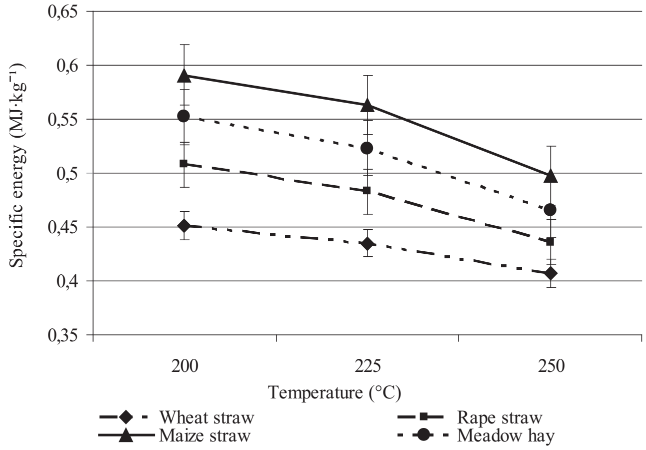

Fig. 4. Effect of temperature on specific energy

Discussion

Biomass of plant origin has a relatively high calorific value and is a valuable energetic material, which can be converted into biofuels. The quality of the produced solid biofuels and the energy consumption of the pressure agglomeration of plant biomass (forming into pellets, briquetting) depend on several parameters in the process (including the moistness level of the raw material, the process temperature, the size of the particles of the material, its chemical composition), and of the equipment (types of agglomerating elements and devices, their working parameters, system geometry, etc.). The similar observation was reported by Hejft (2013); Kallyan and Morey (2009); Niedziółka et al. (2012); Szymanek and Kachel-Jakubowska (2010).

According to Hejft (2013), the plant materials subject to pressure agglomeration should have a moistness level between 8% and 15%. Greater material moisture has a negative effect on the process and the quality of the product. This mainly concerns the drop in the density, the kinetic durability, and the calorific value of the pellets and briquettes. Zarajczyk's research (2013) also shows that the calorific value of the pellets made from plant-based raw materials depends on their moistness, and was between 14.7 MJ kg^{-1} for wheat straw and 15.9 MJ kg^{-1} for rape straw. Meanwhile, in our tests, the moistness of the compacted plant-based raw materials was between 10.2% and 14.1%, while their calorific value was between 16.3 and 17.9 MJ kg^{-1}.

According to many authors (Franke and Rey, 2006; Gil et al., 2010; Hejt, 2011), some of the types of waste in the densified mixture can play the role of a natural binder and make the produced pellets more durable, and have a positive effect on the power demand of the process of forming pellets. The mechanical durability of the produced pellets and briquettes was considerably influenced by the used plant-based raw materials, the types of the devices, and the agglomeration parameters. The lowest mechanical durability was shown by rape-straw pellets (82.4%), while the highest was shown by meadow-hay pellets (95.5%). In turn, the lowest mechanical durability was shown by rape-straw briquettes (58–81%), while the highest was shown by maize straw briquettes (70–95%). The results of the conducted tests show that the rising temperature of the briquetting process is accompanied by a growth of the mechanical durability of the briquettes by 23–25%.

Numerous researchers state that the forming of pellets and briquetting processes consumes a high amount of energy in biofuel production. According to Hejft (2011); and Zarajczyk (2013), depending on the processed material, the energy consumption of the agglomeration process can range from 36-54 to 288-360 MJ t^{-1}. This is proven by the results of our tests on the energy consumption of pellet and briquette production. The average values of energy consumptions for pellets were from 0.46 MJ kg^{-1} for rape straw to 0.53 MJ kg^{-1} for meadow hay. For briquettes, the lowest value of specific energy was recorded for wheat straw compacted at a temperature of 250°C (0.39 MJ kg^{-1}), while the highest was recorded for maize straw compacted at a temperature of 200°C (0.59 MJ kg^{-1}). Other authors (Frączek et al., 2010; Hejft, 2011; Szpryngiel et al., 2010; Thek and Obernberger, 2012) also believe that the rising temperature during the agglomeration process has an impact on the drop of the energy consumption in the production of solid biofuels.

Conclusions

The statistical analysis showed significant differences in case of mechanical durability of produced pellets from tested plant materials. The lowest values of mechanical durability were obtained in case of pellets from rape straw (about 82%), while the highest in case of pellets from meadow hay (about 92%).

Analysis of variance showed that both the used plant materials and the temperature in the compacting chamber briquetting presses have a statistically significant influence on mechanical durability of produced briquettes. The lowest mechanical durability was noted in case of briquettes from rape straw compacting at a temperature of 200°C (about 58%) and the highest for maize straw briquettes at a temperature of 250°C (about 95%).

Analyzing the results study found that the specific energy of pellets production process depended on type of agglomerated plant materials. The smallest specific energy was during rape straw forming into pellets (0.46 MJ kg^{-1}), while the largest in case of produced pellets from meadow hay (0.53 MJ kg^{-1}).

The specific energy of briquettes production depended on both, the type of plant materials, as well as the temperature in the compacting chamber briquetting presses. The lowest values of the specific energy reported for wheat straw briquettes (0.39–0.45 MJ kg^{-1}), and the highest for briquettes from maize straw (0.50–0.59 MJ kg^{-1}). With increasing temperature from 200 to 250°C, the decline in specific energy was contained within the 17–19% for all plant materials used for briquettes production.

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