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THE IMPACT OF NEW CONSTRUCTIONAL SOLUTIONS OF PELLETING DEVICES ON PROPERTIES OF THE PRODUCED PELLETS

Summary

The paper presents results of study of the pellets made of agricultural biomass. In the tests wheat straw was used and then ground raw materials were concentrated using two types of pelleting machines: with flat matrix and driven by compacting rollers as well as with ring matrix. The research methodology consisted of measurements of physicochemical properties of pellets, i.e. humidity after compaction, bulk density, and mechanical stability factor. Calorific value, ash content, and chemical composition of the raw material were also specified. Average humidity of the raw material ranged from 10.30% for ring press to 10.77% for flat press. The pelleting process changed the water content in a final product causing statistically significant differences between pelleting devices applied. The bulk density of pellets in both machines did not differ considerably and amounted to 541.77 kg·m^{-3} for ring press and to 544.21 kg·m^{-3} for flat press. Calorific value of the produced pellet in both cases was above 15 MJ·kg^{-1}. Applying new constructional solutions in a form of two pelleting device types, allowed for obtaining product that was characterized by high mechanical durability greater than 95%.
***Key words**: pellets, innovation, pelleting machines, bulk density, calorific value*

WPŁYW NOWYCH ROZWIĄZAŃ KONSTRUKCYJNYCH GRANULATORÓW NA WŁAŚCIWOŚCI WYTWARZANYCH PELETÓW

Streszczenie

W pracy przedstawiono wyniki badań peletów z biomasy pochodzenia rolniczego. Do analiz użyto słomy pszennej, a następnie rozdrobnione surowce zagęszczano przy użyciu dwóch rodzajów granulatorów: z matrycą płaską i napędzanymi rolkami zagęszczającymi oraz z matrycą pierścieniową. Metodyka badań obejmowała pomiary właściwości fizykochemicznych peletów, tj. wilgotność po zagęszczeniu, gęstość usypową i współczynnik trwałości mechanicznej. Określono wartość opałową, zawartość popiołu oraz skład chemiczny surowca. Średnia wilgotność surowego materiału mieściła się w granicach od 10,3% dla prasy pierścieniowej do 10,77% dla prasy z matrycą płaską. Po procesie granulacji zawartość wody w gotowym produkcie uległa zmianie powodując statystycznie istotne różnice między stosowanymi granulatorami. Gęstość usypowa peletów w obu prasach nie różniła się znacząco między sobą i wynosiła 541,77 kg·m^{-3} dla prasy pierścieniowej oraz 544,21 kg·m^{-3} dla prasy z matrycą płaską. Wartość opałowa uzyskanych peletów w obu przypadkach wynosiła powyżej 15 MJ·kg^{-1}. Wykorzystując nowe rozwiązania konstrukcyjne w postaci dwóch granulatorów uzyskano surowiec charakteryzujący się wysoką trwałością mechaniczną, wynoszącą w obu prasach powyżej 95%.
***Słowa kluczowe**: biomasa, pelety, innowacja, peleciarki, wilgotność, wytrzymałość mechaniczna, wartość opałowa*

1. Introduction

For efficient use of biomass, one should focus on maintaining the basic physical parameters, which include: particle size, actual density, bulk density, porosity, hardness, durability, moisture content, or the rate of moisture sorption [6]. Control of the processes is related to its granulation, which allows to increase its density and energy characteristics, while also contributing to minimize costs, transport and storage surface for the raw material [4, 8, 17, 18]. Compacting the biomass through its pelleting can remarkably increase its bulk density from 40-250 kg·m^{-3} up to 600-800 kg·m^{-3} [13]. Such produced pellets are the most desirable and versatile form of biomass conversion that is used both in large-scale co-combustion systems and small local boilers [2]. The pelleting process (granulation) is aimed at achieving pellets with normalized characteristics (cylinder of 5-40 mm length and 6-12 mm diameter). The product has to meet the criteria related to physicochemical properties, including shape, moisture content, density, calorific value, mechanical durability, as well as carbon, hydrogen, nitrogen, and sulfur contents in accordance with the norm PN-EN 14961-6 "Solid bio-fuels – specification of fuels and classes" [3, 12, 15].

Knowledge of the basic physicochemical properties of the biomass is necessary for the correct selection of equipment design, and achieving a high-quality product. The physical properties of pellets made of the biomass also depend on the variable parameters of the pelleting process, such as speed, temperature, pressure, and process time [16].

Biomass, in its primary form, has a wide range of moisture content ranging within 25-60% [18]. Based on numerous studies, it can be concluded that the moisture content in raw materials has a significant effect on the physical properties of mechanical strength and the calorific value of processed biomass [8, 9]. In the case of the use for energy production, calorific value is of great importance, because it depends on the chemical composition of the raw material, its moisture content, type of material and preparation techniques [7, 8]. It can range from 6-8 MJ·kg^{-1} for biomass with moisture of 50-60% through 15-17 MJ·kg^{-1} for pre-dried biomass of moisture about 10-20%, up to 19 MJ·kg^{-1} for completely dried biomass. The individual components of solid fuels, which comprise the biomass, are different and depend on the type of fuel and the coalification degree. With increasing the metamorphism of raw material, there is a significant increase in carbon content, a decrease in oxygen and a small reduction in the hydrogen content. Proportions of nitrogen and sulfur, in practice do not depend on the carbon content in fuel, and the other elements present in the biomass in small amounts in form of mineral substances [21]. Quantity of ash from the biomass causes many problems in a direct combustion process. The melting of ash increases the tendency of depositing on the cooking surface in a form of slag. Presence of slag and other contaminants can cause a reduction in efficiency of heating installations [22].

The aim of the study was to compare two pelleting devices of new construction and analysis of the resulting material in the form of pellets with a diameter of 8 and 20 mm, in terms of moisture content, mechanical strength, calorific value, and ash content. The analyzes also included elemental composition, in particular, carbon, hydrogen, sulfur, and nitrogen contents in tested material.

2. Materials and methods

Raw material

The study material consisted of two wheat straw samples weighing 10 kg each, which were subjected to pelleting. The first sample came from the company Ursus SA in Dobre Miasto, and the other from the Malopolska Plant Breeding in Krakow, Division Palikije. In both cases, the test material was stored under storage conditions at ambient temperature of 20°C and relative atmospheric humidity of 70-80%. Two types of new-construction pelleting machines were used to produce pellets: one was equipped with the ring-matrix with open compacting chamber and was included in the technological line for pellets production, while the other solution comprised of laboratory-scale flat-matrix device owned by Department of Machinery Exploitation and Management of Production Processes, University of Life Sciences in Lublin (fig. 1). Prior to pelleting process, the straw was preliminarily cut in RZ01 chopper into fractions of the lengths from 20 to 40 mm, then supplied to the beater mill HM05 and broken into fractions of the lengths from 12 to 15 mm (Table 1). Relative moisture content W_t was determined in accordance with the norm PN-EN 14774-2:2010 applying gravimetric method. Moisture measurements were made in fiver replicates.

Determinations of carbon C_t and hydrogen H_t contents were made according to CEN/TS 15104:2006 using automatic IR analyzer, nitrogen N according to CEN/TS 15104:2006, and total sulfur S_t according to PN-G-04584:2001 by means of IR analyzer measurement at Central Laboratory of Zakłady Pomiarowo-Badawcze Energetyki „Energopomiar" Sp. z o.o., Gliwice.

Source: own work / Źródło: opracowanie własne

Fig. 1. Pictures of the used pelleting machines: a) with flat matrix, b) with ring matrix

Rys. 1. Zdjęcia zastosowanych peleciarek: a) z matrycą płaską, b) z matrycą pierścieniową

Table 1. Technical specification of the pelleting machines

Tab. 1. Specyfikacja techniczna zastosowanych maszyn

Parameters	Unit	Pelleting machine	
		Flat-matrix	*Ring-matrix
Efficiency	kg·h^{-1}	150	600
Dimensions	LxBxH	1300 x 650 x 1020	2820 x1480 x 1650
Matrix diameter	mm	225	-
Diameter of matric perforation	mm	8.0	25.0
Matrix thickness	mm	25	-
* Inner diameter of matrix	mm	-	644
* Outer diameter of matrix	mm	-	900
Length/height of push rollers	mm	50	-
* Height of matrix	mm	-	128
* Working height of rollers	mm	-	76
Diameter of push rollers	mm	100	240
Number of rollers	pcs.	2	4
Rotational speed of rollers/head	rpm	110	38
Engine power	kW	7.5	55
Weight of pelleting machine	kg	215	~ 3250

Source: own work / Źródło: opracowanie własne

The calorific value of the produced pellets was calculated from the heat of combustion as determined by calorimetric technique in isoperybolic Parr 6400 Calorimeter according to the norm PN-EN 14918:2010. The test consisted in complete combusting the samples of 1.5 g weight (+/- 0.0002 g) in oxygen atmosphere under pressure of 3 MPa in a bomb calorimeter immersed in water.

Mechanical strength of pellets was tested in accordance to the norm PN-EN 15210-1, using the standalone rotational tester with three containers of normalized dimensions rotating with angular speed of 5.22 rad·s^{-1} for 600 s; the mechanical strength indicator for pellets was calculated using the formula (1):

$$D_U = \frac{m_A}{m_E} \cdot 100 \; \% \qquad (1)$$

where:

D_U - mechanical strength indicator for pellets [%],
m_A – weight of pellets after durability test [g],
m_E – weight of pellets prior to durability test [g].

The bulk density was determined using the cereal density-meter of 861 g weight. It was made by free pouring of pellets from the hopper with a height of 100 mm into the measuring vessel with a capacity of 0.5 dm^3. After filling the vessel and removing the excess of product, it was weighed on WPE 200 scales with accuracy of ±0.1 g. The bulk density of pellets was calculated from the following formula (2):

$$\rho = \frac{m_z - m_n}{V_n} \quad [kg \cdot m^{-3}] \qquad (2)$$

where:

m_z – weight of vessel with pellet sample [kg],
mn – weight of empty measuring vessel [kg],
Vn – capacity of measuring vessel [m^3].

Results are presented as means ± standard deviation from five replicates of each experiment. The measurement results for calorific value, bulk density and mechanical strength of pellets were examined statistically using analysis of variance (ANOVA), Pearson correlation, post–hock Tukey's test, with a level of significance of a $p < 0.05$ with the assistance of Statistica 10 software.

3. Results and discussion

3.1. Effect of moisture on durability and calorific value of pellet

Calorific value of a biomass is an important parameter that describes the energy value and thermal conversions of combustion systems [5, 27]. Its level depends on the type and amount of combustible components in the fuel and the moisture content. In contrast, the moisture content is one of the fundamental parameters determining the suitability of fuel, affecting its calories and playing a significant role in combustion process and pollution emissions [10]. This value is also important in assessing the sales and storage opportunities. Its high content in the biomass reduces the calorific value. Combustion of fuels with high moisture content may lower the combustion temperature, causing difficulties in its complete combustion. Durability of pellets can be defined as the strength ability of granules to destructive loads and forces during transport [11]. The mechanical stability is considered to be sufficiently high when the calculated value is greater than 80% [6].

Table 2 shows the results of the basic parameters for the initial moisture content prior to compaction and after pelleting the wheat straw, as well as parameters after compaction process related to their stability and calorific value. The average value of the raw material humidity ranged from 10.30 for the ring press to 10.77% in the case of a flat press. Straw after compaction had the moisture contents 7.26 and 9.93%, respectively. The resulting stability of pellets was in the range of high strength and in both cases was more than 95%. This result can be comparable with the results obtained by other researchers who received similar values for pellets (up to 97%) [24]. Analysis of the energetic characteristics of tested straw revealed that calorific value of pellets amounted to 15.71 and 15.08 MJ·kg^{-1}, respectively.

In order to confirm the relationship between two variables, the statistical analysis based on the Pearson correlation coefficient at a significance level <0.05 for normal distribution of measurement results, was performed. The analysis related to two variables - the type of pelleting device and mechanical stability of the pellets - showed a negative correlation at the significance level (-0.760). The same analysis for moisture after granulation and mechanical stability also showed strong, statistical significance at the significance level (0.736). Analysis of the study results using the post-hoc Tukey test also showed that there are statistically significant differences for the resultant pellet moisture between used press types.

3.2. Effect of moisture on density of pellets

Low biomass density makes its transport to large distance difficult and requires large area of storage. The bulk density of straw is 20-50 kg·m^{-3}, when compared to brown and hard coal, for which these values are from 800 to 1200 kg·m^{-3} [14, 20], makes that the transport costs become higher [4]. Analysis of the bulk density of pellets (Table 2) in both press types did not significantly differ and amounted to 541.77 kg·m^{-3} for the ring matrix and to 544.21 kg·m^{-3} for the flat matrix. These results appeared to be slightly higher than those reported by Theerarattananoon et al. [25], who measured density for the wheat straw as 495.8 kg·m^{-3}. According to the requirements of European standards, the bulk density should be higher than 500 kg·m^{-3} [25]. The analysis of the linear correlation between the type of pelleting machine and bulk density showed no strong correlation (-0.181). A similar situation was also observed for moisture after granulation and bulk density (-0.262). The post-hock Tukey tests also showed no statistically significant differences between the resulting bulk density and the type of the pelleting device used.

3.3. Analysis of the ashes

Identification and characterization of the chemical composition and phases of a given solid fuel is the first and most important step in the use of such fuel. This composition is a unique code that characterizes the basic properties, quality, potential use, and environmental problems that may arise [26]. Each fuel consists of a combustible part and a ballast (minerals, moisture) and the non-combustible gaseous components, e.g. nitrogen or carbon dioxide. Chemical and physical composition of a substance is the most important information determining its suitability as a fuel. For proper combustion, it is needed to meet the conditions of good mixing the fuel with air and a suitable temperature in the furnace.

Table 2. Physical properties of pellet biomass
Tab. 2. Właściwości fizyczne peletów z biomasy

Product	Press type	Moisture before compaction (%)	Moisture after compaction (%)	Bulk density (kg·m^{-3})	Mechanical durability (%)	Calorific value (MJ·kg^{-1})
Wheat straw pellets	Flat matrix	10.77±0.23	9.93±0.12	544.21±6.34	95.86±0,09	15.08±0.02
	Ring matrix	10.30±0.12	7.26±0.01	541.77±10.26	95.63±0.06	15.71±0.13

Source: own work / Źródło: opracowanie własne

Table 3. Elemental analysis of the ashes (carbon free basis)
Tab. 3. Analiza elementarna popiołów

Product	Press type	Carbon (%)	Hydrogen (%)	Nitrogen (%)	Sulfur (%)	Ash (%)
Wheat straw pellets	Flat matrix	46.97±0.06	5.71±0.01	1.19±0.01	0.12±0.01	5.66±0.01
	Ring matrix	44.74±0.01	5.45±0.01	0.74±0.01	0.10±0,00	6.55±0.48

Source: own work / Źródło: opracowanie własne

The type and quality of fuel affects their behavior during combustion. The elemental composition of the biomass used in the power industry, in quality terms, is the same. Differences occur while shares of individual chemical elements and compounds. The biomass has an average of two times less carbon as well as less sulfur and nitrogen as compared to fossil fuels, and consequently, it has a high content of volatile matter.

In order to verify the differences between the analyzed samples of wheat straw subjected to the pelleting process, the achieved pellets were subject to chemical analysis (carbon, hydrogen, nitrogen, sulfur contents) aimed at checking whether different origin of the material affects its chemical composition (Table 3). Based on these results, it can be concluded that the quantities of analyzed elements, and crude ash generated from combustion of 2 kg straw pellets, were a little different, although these differences were statistically significant. The ash content produced from the same material in the case of flat matrix was 5.66%, while for the ring matrix 6.55%. According to Bakisgan [1], ash content for the wheat straw amounted to about 7.9%, while Skonecki [23] reported average value of 4.93%. Such differences can be explained by the diversity of relations between soil composition and type, climate, and genetic characteristics of raw material. Similar quantities of macroelements in crude ash made of wheat straw were recorded in both cases in the following sequence: C>H>N>S.

The statistical analysis concerning linear correlation coefficient at the level of $p<0.05$ showed a strong negative correlation (-0.837) between the moisture content after the pelleting process and the resulting ash content, confirming that the higher water content of the pellets, the lower ash content. A strong positive correlation coefficient was also noted for the moisture content after the pelleting process and the content of carbon in combusted pellets (0.993) as well as moisture content and the hydrogen content in the combusted pellets (0.967).

4. Conclusions

Based on the tests, data on general physicochemical properties of the pellets produced from wheat straw, were achieved. Using new constructional solutions in the form of two pelleting machines, obtained product from both presses was characterized by high mechanical stability more than 95% with minor differences that after analyzing the Pearson correlation showed a strong negative correlation at the level of -0.760 between variables describing the type of press and the resulting durability.

Recorded bulk density did not considerably differ (statistically insignificant differences), although in the case of the ring matrix, it was characterized by lower parameter amounting to 541.77 kg·m^{-3}.

Moisture content in pellets considered in a view of applied pelleting devices was greatly diverse (statistically significant), which was for flat matrix 9.93%, and for ring matrix 7.26%.

Calorific value depending on the moisture content in pellets showed a weak negative correlation at the level of -0.262. The analysis of linear correlation coefficient confirmed a strong negative dependence (-0.837) of water content in pellets on the recorded ash content, which means that the amount of ash decreased along with the increase of pellet moisture.

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