POLITYKA ENERGETYCZNA – ENERGY POLICY JOURNAL

2020 ✦ Volume 23 ✦ Issue 1 ✦ 75–86

DOI: 10.33223/epj/119620

Tomasz Mirowski[1], Marta Jach-Nocoń[2], Iwona Jelonek[3], Adam Nocoń[4]

The new meaning of solid fuels from lignocellulosic biomass used in low-emission automatic pellet boilers

Abstract: The energy obtained from biomass in the global balance of energy carriers is the largest source among all RES. It should be borne in mind that the share of biomass as an energy carrier in the total balance is as much as 14%. The basic sources of renewable energy used in Poland are the wind power industry and biomass. Organic chemical compounds are the source of chemical energy for biomass. The biomass can be used in a solid form (wood, straw) or after being converted to liquid (alcohol, bio-oil) or gas (biogas) form.

Pellets, meaning, the type of fuel of natural origin created from biomass compressed under high pressure without the participation of any chemical adhesive substances are recognized as the most common and available grades of biomass. Wood pellets manufactured from sawdust, shaving, or

✉ Corresponding Author: Tomasz Mirowski; e-mail: mirowski@min-pan.krakow.pl

[1] Mineral and Energy Economy Research Institute, Polish Academy of Sciences, Kraków, Poland; ORCID iD: 0000-0003-4897-9142; e-mail: mirowski@min-pan.krakow.pl

[2] Department of Geochemistry, Mineralogy and Petrography, Faculty of Earth Sciences, The University of Silesia in Katowice, Poland; P.P.U.H. Zamech Zygmunt Nocon, Czeladź, Poland; ORCID iD: 0000-0003-0594-2366; e-mail: marta@zamech-czeladz.pl

[3] Department of Geochemistry, Mineralogy and Petrography, Faculty of Earth Sciences, The University of Silesia in Katowice, Poland; ORCID iD: 0000-0002-9876-9007; e-mail: iwona.jelonek@us.edu.pl

[4] Department of Geochemistry, Mineralogy and Petrography, Faculty of Earth Sciences, The University of Silesia in Katowice, Poland; P.P.U.H. Zamech Zygmunt Nocon, Czeladź, Poland; ORCID iD: 0000-0003-3745-114X; e-mail: a.nocon@budmetnocon.pl

woodchips are the most popular type of pellets on the market. Fuel created in the form of granules is very dense and can be manufactured with low humidity content, which translates into an exceptionally high burn efficiency.
The authors of this article burned agro pellets from *Miscanthus giganteus* without additives and with solid catalyst and conducted a series of tests that determine the impact of boiler settings (blast power, time of feeding, chimney draft) on the process of burning fuel in real conditions. A solid catalyst was used to improve combustion conditions in one of the fuels. The catalyst burns carbon monoxide and reduces nitrogen oxides. The results in the form of observation of selected parameters are summarized in the table.

Keywords: low emission, CO reduction, NO_x reduction, *Miscanthus giganteus*, class 5 boiler

1. Introduction

1.1. The meaning of biomass in energy–mix

Biomass is one of the basic sources used for energy production – 14% of the world's energy demand comes from biomass. This is in fourth place after crude oil, natural gas and coal in the global energy production structure. Biomass is also one of the zero–emission technologies – the amount of carbon dioxide during combustion is the same as its amount absorbed during the growing cycle of plants used for fuel. The use of biomass fuels in the energy industry, heat industry and individual heating reduces negative external effects resulting from the use of fossil fuels, and thus biomass can be considered as a technological nutrient in the circular economy model. The production of biomass also ensures a country's economic safety and trade balance through the production process itself, which makes it one of the autonomous sources of energy, and may be a strategic energy resource, in some cases. A good example is Lithuania. From 2000 to 2016, biomass use in the district heating sector (DH) increased from 2 to 65% – the share of biomass used in DH has exceeded the share of imported gas (LITBIOMA 2019). In Austria, the share of "biofuels" in heat production in 2016 was around 43% (natural gas 35.5%, waste 10.7%, oil 6%). In Finland, "biofuels" represent a 40% share in heat production, followed by coal at around 34%, natural gas at 14% (IEA Statistics 2018). Figure 1 shows the shares of individual RES in the EU-28 countries converted to primary energy. The share of biomass and bio–waste in heat production in most European Union countries exceeds 50%.

Taking social factors into account, biomass production has an effect on rural area management and can help solve problems related to the depopulation of rural areas by providing work in this agricultural sector, and through the profitability of growing crops intended for biomass production for fuel purposes.

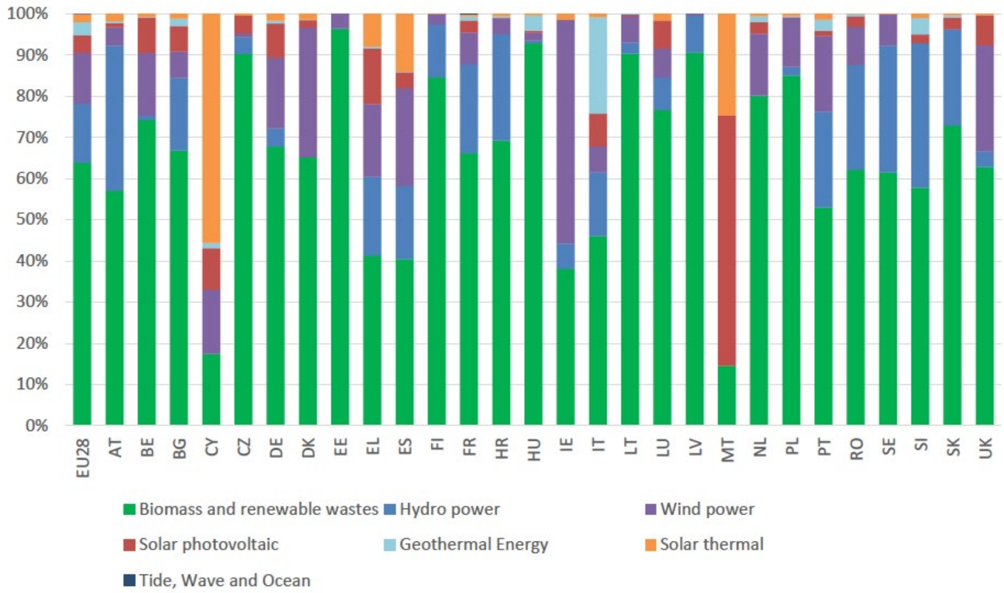


Fig. 1. The share of the different renewable energy sources out of total primary energy production of renewables in EU28 Member States in 2016 [%] (Bioenergy Europe 2018)

Rys. 1. Udział odnawialnych źródeł energii w całkowitej produkcji energii pierwotnej z OZE w 28 państwach członkowskich UE w 2016 roku [%]

1.2. The problem of smog and solid fuels from biomass

The quality of solid fuels burnt in households in such countries as Poland, the Czech Republic or Slovakia has a significant effect on the low emission phenomenon, and the improvement of the air quality in Poland and has become a priority for many local communities in cities and communes over the past few years. Low emissions from the municipal and housing sector in Poland in the last few years have reached very high levels, exceeding the standards adopted for air (50 μg/m^3 per day) (KPOP 2015). In 2010–2016, households consumed from 8.9 to 10.8 million Mg of coal annually, and their share in the consumption of coal in the municipal and household sector changed in the range of 77–81% (Stala-Szlugaj 2018). The use of poor quality coal in old boilers with manual loading, which do not meet the PN-EN 303-5:2012 standard for class 5 (Norm 2012) and ecodesign (Ecodesign Directive 2015), contribute significantly to the growth of low emissions. Low emissions have a significant impact on air quality, as a low-emission source often leads to a high concentration of pollutants in zones occupied by people. Research in the field of air pollution inventorying shows an increase in dust emissions (2012–2013) from combustion processes outside the industry, mainly from households. The emission of carbon monoxide (CO) in 2013 from combustion processes outside the industry amounted to 64% and dust to 50%. This clearly indicates a wrong technique of fuel combustion in this sector (Mirowski and Maczuga 2017; Drobnik et al. 2019).

The basic source of renewable energy used in Poland is solid biomass (71% of primary energy from RES) and wind energy (12%) (GUS 2018). The source of chemical biomass energy is organic chemical compounds that are created thanks to cellular synthesis processes from carbon dioxide and water due to the photosynthesis process on the surface of the Earth. For fossil fuels (hard coal, brown coal), the accumulated solar energy for organic metabolism was "trapped" and had no direct effect on the CO_2 balance in nature at that time.

One of the most popular and available types of fuel from biomass are pellets, a natural type of fuel originating from high pressure compressed biomass without any chemical adhesives. The most popular on the market are wood pellets, produced from sawdust, chips or wood chips. Produced fuel in the form of granules is very compact and can be produced with low moisture content, which has a very high combustion efficiency.

According to EU standards, pellets intended for the individual market in Europe should not contain more than 10% of water, are compact and have a low ash content and CO_2 emissions. Pellets can be made from any type of wood provided that the matrix through which the material passes is made of an appropriate type of steel and in a suitable technology. According to PN–EN ISO 17225–2, wood pellets can be divided into the following classes: A1 – the highest quality pellets for use in boilers and furnaces heating households, A2 – pellets for less demanding installations; B – pellets made of unprocessed wood without heavy metals. Pellets with DIN Plus and EN Plus A1 certificates are the most popular on both domestic and foreign markets (ISO_Standard 2014). Imported pellets from sunflower husks are also available on the Polish market but their physical and chemical properties do not meet DIN Plus and EN Plus standards. Energy plants (such as Miscanthus giganteus, hemp willow) are interesting in terms of the utilization of agricultural potential and their use has been widely researched and described in research works (Borkowska and Molas 2013; Mudryk et al. 2018) and EU projects (OPTIMISC 2016).

The aim of the authors is to determine the effect of automatic boiler settings on factors that are not directly related to boilers, such as: chimney draft, primary air temperature, physical and chemical properties of fuel, ash content. For this purpose, biomass burning tests in the form of *Miscanthus* pellets were performed, measuring the actual exhaust emission in a laboratory with an installation simulating the actual boiler operating conditions.

The paper presents the first part of the research, which concerns the fan characteristic and its modulation work.

2. Scope of research

2.1. Fuel

Two types of fuel were prepared for the purposes of the research. The first type is pellets from *Miscanthus gignteus* without additives. The second type of fuel is pellets from *Miscanthus giganteus* with a refining addition – a solid catalyst that improves the combustion process of carbon monoxide and reduces NO_x.

One of the most important reasons for choosing the Miscanthus energy plant was its CO_2 absorption during growth. *Miscanthus giganteus* is a C–4 photo–synthetic plant. The C–4 plants have a high carbon dioxide fixation rate, which allows for high rates of photosynthesis. The C4-plants can, therefore, grow very quickly (Sørensen et al. 2008). Older specimens are resistant to low temperatures and have high yields up to 25 t/ha. The calorific value of Miscanthus is 14–17 MJ/kg. Due to the longevity of the plantation (15–20 years), as well as high biomass productivity, it is considered a very valuable, alternative energy source for the local energy community. Table 1 summarizes the most important physical and chemical parameters characterizing plants of the *Miscanthus giganteus* species (Kacprzak et al. 2012).

Table 1. Characteristics of *Miscanthus* pellets

Tabela 1. Charakterystyka pelletu z miskantusa

Calorific value [MJ/kg]	17.2
Moisture [%]	6.5
Ash [%]	1.7
Volatile matter [%]	75
Density [kg/m^3]	600

2.2. Methods and equipment

For proper operation, boilers with automatic fuel dosing require setting fuel feed time (fuel dose) parameters, break in its feed and the amount of air fed to the burner. Individual settings in the boiler controller input by the user often cause irregularities in the fuel combustion process and, consequently, energy losses, ash increase, higher emission of fumes and user dissatisfaction with the boiler. The authors have attempted to investigate the dependence of the amount of air supplied to the pellet burner on the combustion process in a 25 kW heating boiler with an automatic fuel delivery system and chamber cleaning. The research system is shown in Figure 2. The research was conducted in a real combustion laboratory of solid fuels for 5 days (42 hours). The following equipment was used to measure the temperature in the fuel oxidation zone:

- two thermocouples up to 1500°C with digital temperature measurement,
- TESTO 330 exhaust gas analyzer,
- TESTO 380 dust meter,
- 35W power and 50 Pa compression modulated radial fan (100 m^3/h).

Fig. 2. Cross section of the boiler and research installation and boiler adapted to make measurements at Zamech labolatory

Rys. 2. Przekrój kotła oraz stanowisko badawcze z kotłem przystosowanym do badań w laboratorium firmy Zamech

The measuring equipment was used to verify the acceptable values indicated in the PN-EN 303:5–2012 standard, as well as ecodesign recommendations for NO_x emissions (200 mg/m^3).

3. Discussion of results

The non-linear characteristics of the fan operation indicates the need to divide the measurements into a constant medium compression part at the level of 136 Pa in the air stream range of 10–40 m^3/h (yellow field in Fig. 3) and a linear decrease from 135 Pa to 20 Pa in the stream range of 40–94 m^3/h (orange field in Fig. 3).

Seven characteristic points in which measurements were made: flue gas stream and temperature, temperature in the ultraviolet and reduction zone, were determined.

The testing range for the 20–100 m^3/h range was reduced to an air flow of 20–60 m^3/h based on the results obtained from the exhaust gas analyzer and dust meter. The figure 3 summarizes the values of determinants of optimal combustion parameters averaged from all measurements. Determinants are lambda, NO_x and CO converted to 10% O_2 measured for characteristic points of the fan setting, i.e. 20, 40, 60% of the fan power.

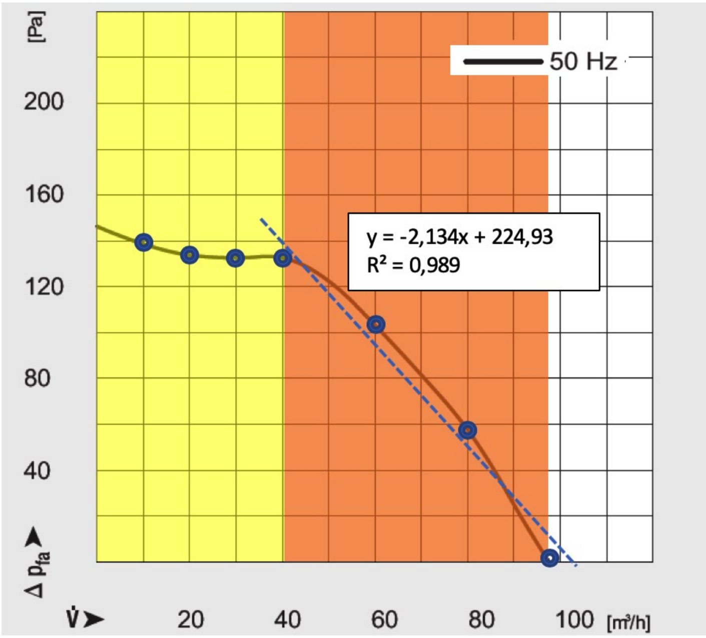
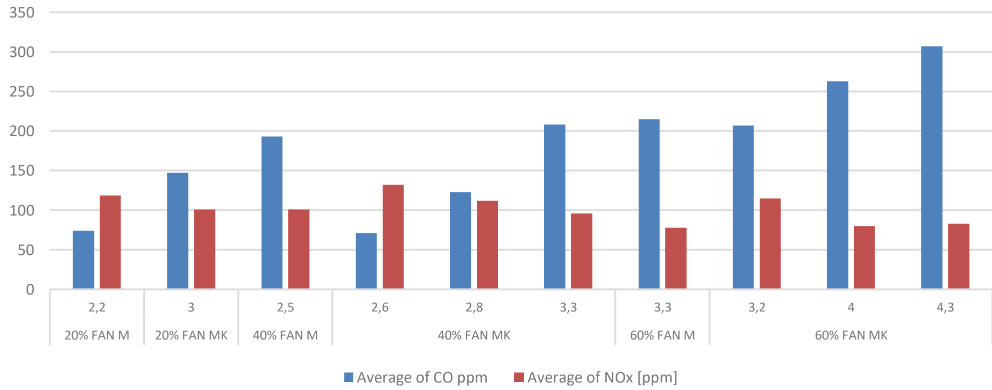


Fig. 3. Fan operation characteristics

Rys. 3. Charakterystyka wentylatora



Comment:
The lambda value is given in the first row of the x axis
XX% FAN M means XX% of fan power with *Miscanthus* pellets without additives.
XX% FAN MK means XX% of fan power with *Miscanthus* pellets with solid catalyst.

Fig. 4. Averaged values of determinants of optimal combustion parameters NO_x, CO, Lambda <2,2–4,3> in fan operation range 20–60% for *Miscanthus* pellets with– and without solid catalyst

Rys. 4. Średnie wartości determinantów optymalnych parametrów spalania NO_x, CO, Lambda <2,2–4,3> w zakresie pracy wentylatora 20–60% dla pelletu z miskantusa z katalizatorem stałym i bez katalizatora

A solid catalyst was used to improve to combustion process; burns carbon monoxide and reduces nitrogen oxides. The results in the form of observation of selected parameters are summarized in Table 2.

Table 2. Test results

Tabela 2. Wyniki przeprowadzonych badań

Changing the input quantities	Observation
Airflow increase in the range of 20–40% of fan power	CO_2 emission decreases from 600 mg/m^3 to 400 mg/m^3. NO_x emission is kept at a level not exceeding 100 mg/m^3. Temperature rises in the flame zone to 1100°C.
Switch from modulation mode from 30 to 60%	Exhaust temperature stabilization. The temperature in the flame zone is 1150–1200°C. The amount of NO_x increased to 150–160 mg/m^3. CO emission does not exceed 350 mg/m^3. The setting "40% FAN MK" achieved the best results.
Work in the 20% mode	NOx increases to 380 mg/m^3, temperature in the flame zone is 770–850°C. The test with "20% FAN M" setting ended twice with stopping the combustion process in the boiler. The test with "20% FAN MK" setting was successful.

The emissions of gases and particulates have been investigated using two boiler control methods. The first was the regulation of operation using the PID algorithm. The PID controller is a combination of proportional, integral and derivative control mechanisms. The combination of these three components effectively stabilizes the variable manipulated at the set point (the temperature of the heating medium). The second method of boiler control was the modulation of boiler power. For this purpose, a control algorithm implemented for the TECH–ST9704 boiler controller was used, which enables 3 stages of modulation of 100, 60 and 30% of air grading in a wide range of secondary air flow velocities. The air grading algorithms have been used to test the burning rate, temperature in the primary and secondary zones, as well as NO_x, CO and TSP emissions, taking the stoichiometric ratio of air to fuel into account. A similar methodology of testing on a 500 kW boiler was adopted at the work by (Sippula et al. 2017).

These results underline the need for further research using CO sensors and temperature to better understand the effect of air grading on NO_x and CO emissions and the temperature in the flame zone that affects the amount of unburned fuel and ash quality.

Summary

More efficient biomass combustion while reducing emissions of gases and particulate matter can be ensured by applying the precise grading of the amount of air for combustion. The value of the tested NO_x emission for selected boiler controller settings confirms the results obtained at the work by (Liu et al. 2013), where the result of the experiment was the determination of NO_x emissions in various air stage configurations, as well as the varying proportions of primary to secondary air. The influence of air gradation on temperature, combustion rate, gas and particulate emissions was assessed on the basis of the selected primary air flow rate and the secondary air flow rate range based on calculations. The quality of ash was measured during the combustion process through two thermocouples.

There is a compromise between the emission of nitrogen oxides (NO_x) and carbon monoxide (CO). Reducing the excess of air reduces NO_x emissions, but also increases the emissions of unburned substances. This can be assessed by looking at the lambda factor in Figure 3. The capacity increases as the excess of air decreases until the losses due to incomplete combustion become too high. Often, the high NO_x emission in today's pellet burners can be significantly reduced by well-known techniques such as air grading. The emissions of NOx and CO can also be reduced by using small amounts of inorganic salt as a solid catalyst.

The development of various chemical sensors is very intense. As well the availability of CO and OGC sensors on the market gives the possibility of using them in class 5 pellet boilers. These sensors, together with the lambda probe, can provide effective boiler control for optimal efficiency in terms of emissions and efficiency. The critical parameters for minimizing NO_x emissions from pellet burners are examined in detail. The test results of the new sensor are also reported. The work by (Eskilsson *et al.*, 2004), has shown that relatively simple modifications of the structure can significantly reduce NO_x emissions in biomass burners in the form of pellets.

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Nowe znaczenie paliw stałych z biomasy lignocelulozowej stosowanych w niskoemisyjnych automatycznych kotłach na pellet

Streszczenie

Energia uzyskiwana z biomasy w globalnym bilansie nośników energii jest największym źródłem spośród wszystkich OZE. Należy pamiętać, że udział biomasy jako nośnika energii w całkowitym bilansie wynosi aż 14%. Podstawowymi źródłami energii odnawialnej wykorzystywanymi w Polsce są energetyka wiatrowa i biomasa. Organiczne związki chemiczne są źródłem energii chemicznej dla biomasy. Tę z kolei można wykorzystać w postaci stałej (drewno, słoma) lub po przekształceniu w płynną (bioetanol, bioolej) lub gazową (biogaz).

Pellety, czyli rodzaj paliwa pochodzenia naturalnego wytworzonego z biomasy sprasowanej pod wysokim ciśnieniem bez udziału jakichkolwiek chemicznych substancji klejących, są uznawane za najbardziej powszechne i dostępne rodzaje paliwa z biomasy. Pelety drzewne wytwarzane z trocin, wiórów lub zrębki są najpopularniejszym rodzajem peletów na rynku. Paliwo wytwarzane w postaci granulatu (granulek) jest bardzo gęste i może być wytwarzane przy niskiej wilgotności, co przekłada się na wyjątkowo wysoką efektywność spalania.

Autorzy tego artykułu wykonali serię testów spalania peletów agro z trawy *Miscanthus giganteus* bez dodatków uszlachetniających oraz z katalizatorem stałym. Badania miały na celu określenie wpływu ustawień kotła (moc dmuchawy, czas podawania, ciąg kominowy) na proces spalania paliwa w rzeczywistych warunkach. Stały katalizator zastosowano do poprawy warunków spalania w jednym z paliw. Katalizator pozwala dopalić tlenek węgla i redukuje tlenki azotu. Wyniki w postaci obserwacji wybranych parametrów zestawiono w tabeli.

Słowa kluczowe: niska emisja, redukcja emisji CO, redukcja emisji NOx, miskant olbrzymi, kotły 5 klasy