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Analysis of the Energy and Emission Performance of an Automatic Biomass Boiler in the Context of Efficient Heat Management

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Abstract: This paper presents the results of an examination of an automatic biomass boiler identifying its strengths and weaknesses and computing its seasonal energy and emission parameters. The boiler was found to meet the energy and emission requirements for distribution in Poland. The boiler is characterised by good heating efficiency and low dust and carbon monoxide emissions. The aim of this paper is to provide and analyse these parameters, and by doing so classify it in the context of its competitors. The average heating output is 26.86 kW and the thermal efficiency is 87.97%. Carbon monoxide emissions are very low (22.71 mg/m^3). However, nitrogen oxide emissions (187.6 mg/m^3) can be a problem. Filters made out of metalworking waste, i.e., machining shavings, significantly improve the boiler performance, contributing to an increased heat output and efficiency and reduced dust emissions. Compared with other solutions available in the market, the boiler compares favourably in terms of dust and carbon monoxide emissions and is also characterised by similar efficiency, especially with the filters in place. Regarding the context of thermal energy management, the appliance under investigation demonstrates not only favourable energy and emission parameters, but also the potential for the efficient use of thermal energy, which can bring additional economic and environmental benefits.

Keywords: biomass; pellet boilers; energy efficiency; seasonal emissions; boiler efficiency

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1. Introduction

At the moment, there are debates going on in most European countries on the implementation of the European Green Deal and the socio-economic transformation aimed at achieving the climate neutrality of the European Union by 2050 [1–4]. Poland, too, is facing the challenge of having to make extensive changes to its energy generation structure [5,6]. One of the key challenges posed is to increase the share of biomass in Polish district heating as well as individual heating [7,8]. This process is particularly important due to the fact that the vast majority of heat produced nowadays comes from high-emission fossil fuels [9]. In the individual heating sector, as much as 79.3% of heat was produced from fossil fuels [10]. It is therefore reasonable to continuously develop the process of utilising biomass to produce renewable energy in the heating sector in Poland while also continuously implementing measures to encourage the intensification of this development [11,12]. The introduction of new initiatives in this field contributes to the acquisition of new operational

and research experience, especially in the area of biomass utilisation in the individual residential heating sector [13–15].

Currently, an important issue is the assessment of the role of biomass as a fuel in the Polish energy system. Another issue is the identification of the factors shaping the current situation of this raw material and forecasting its use in the near future [16,17]. According to the data compiled by the Energy Regulatory Office (URE) for 2021, biomass accounted for the production of 31,488.5 TJ of heat, i.e., 8.06% of the total heat production in that year. It is worth noting that other renewable energy sources provided only 1049.64 TJ of heat, a negligible share of 0.27% of the total heat production. These figures show the scale of the challenge posed by the excessive use of fossil fuels in the Polish heating infrastructure. Heat production involving these raw materials totalled as much as 341,454.71 TJ, which translates into an impressive 87.42% share of the total annual heat production [18].

It should be emphasised that biomass is now an increasingly widely used primary energy source for heat generation [19–21]. According to the data from the Central Statistical Office, it contributes to a year-on-year increase in the amount of heat produced by several to over ten percent [22]. There are several reasons that have contributed to the popularity of biomass as a fuel. The first of them is the need to reduce atmospheric emissions, which is driven by both environmental and political factors [23,24]. The air quality in Poland leaves much to be desired as confirmed by the research by the World Bank Group indicating that 36 of the 50 most polluted cities in Europe are in Poland [25,26]. The biggest problems are particle air pollution (PM2.5 and PM10) and benzo(a)pyrene pollution [27–29]. One of the main sources of emissions of these substances is the combustion of fossil fuels, especially in inefficient home furnaces of the older type where the temperature of the process is too low, which leads to non-optimal combustion [30,31]. The energy sector also accounts for 91% of PAH emissions into the atmosphere [32], the main cause of which being emissions from the heating of individual flats in buildings using biomass and coal. Households in Poland are the main area where emissions must be reduced. According to the Central Statistical Office, 29.7% of all households use solid fuel boilers and furnaces [33], which means that more than 4 million households in Poland have solid fuel systems installed. Reducing emissions in this sector is becoming a key challenge for the Polish energy sector [34].

A study conducted by Sulaiman et al. (2020) [35] based on an analysis of CO_2 emissions and the consumption of biomass as a fuel between 1990 and 2017 by EU member states showed a clear correlation between an increase in biomass consumption and a decrease in CO_2 emissions. The countries that are likely to benefit the most from an increase in biomass use are the biggest polluters in the EU, such as Germany, France, Spain, Italy and Poland, i.e., countries with a high consumption of fossil fuels. However, the authors emphasise the need for moderation in the use of biomass, especially wood-based biomass, in order to maintain environmental sustainability [35].

Poland also shows a high potential for biomass production, which further supports the development of this sector [14,36]. The potential for obtaining energy biomass, despite being an important issue, has not yet been thoroughly analysed in the context of the requirements of the RED II Directive. Preliminary estimates indicate that it is possible to obtain 25–30 million tons of energy biomass annually. To achieve such results, it is necessary to establish plantations of perennial energy crops, which can yield annual harvests ranging from 8 to 15 tons of dry matter per hectare for a period of 15–25 years, depending on cultivation conditions and the climate [37].

An analysis of the current trends indicates a continued increase in the share of biomass in the total energy consumption in Poland [38–40]. In a report published by Forum Energii, current trends with regard to the installed capacity of pellet boilers in individual heating and biomass boilers in district heating were compared along with a potential option to achieve a 40% share of renewable energy sources in the heating sector. Predictions show that the installed capacity in individual heating might reach approx. 5000 MWt by 2030 at the current rate of development, and that a capacity in the order of 16,000 MWt will be needed to achieve the 40% renewables target. In the case of district heating, the capacity

installed in biomass boilers should be increased to 1000 MWt and a capacity in excess of 3000 MWt will be required to meet the target [10]. These forecasts suggest that biomass will play a key role in the further development of renewable energy sources in Poland [41].

With the aforementioned issues in mind, it is worth noting that there is a wide variety of solutions available in the individual heating sector, ranging from wood gasification boilers through automatic wood pellet boilers to wood chip boilers or boilers fired with pelletized herbaceous biomass [42]. At the moment, automatic wood pellet biomass boilers are the most proven solution and a popular choice in this field [43,44]. This solution is very popular due to its convenience for the user, the automatic feeding of the fuel and the fact that wood pellets are a relatively clean energy source. In addition, this type of boiler is characterised by high thermal efficiency, typically reaching about 85–90% [45].

Additionally, the analysis of the progress in the research and development of biomass boilers both in Poland and abroad indicates a dynamic advancement in this technology in recent years. The increasing interest in renewable energy sources and the need to reduce carbon dioxide emissions are becoming the main drivers of growth in this sector. Consequently, in Poland, research focuses on improving the energy efficiency of biomass boilers and reducing pollutant emissions [46,47]. New standards and regulations promote the use of biomass boilers, particularly in the heating sector [12]. Polish universities and research institutes are carrying out projects aimed at optimising the biomass combustion process and researching new types of fuel, such as pellets and briquettes, which contribute to their improved availability and efficiency [48,49]. On the other hand, in western Europe, particularly in Germany, Sweden and Finland, biomass boiler technology has reached an advanced level [14,50]. In these countries, investments are directed towards modern solutions, such as boilers with automatic fuel feeding, which enable higher efficiency and a lower energy consumption [51]. Research also focuses on diversifying biomass sources and integrating boilers with energy management systems in buildings [52,53].

This study focuses on the analysis of an automatic biomass boiler. This is a model that features some additional improvements that have the potential to increase its energy efficiency and reduce atmospheric emissions. If these innovative solutions prove to be successful and have a positive impact on the boiler's performance, there is scope for further research and development to possibly implement these improvements in other commercially available equipment, too. Therefore, the aim of this article is to analyse the energy and emission performance of the pellet boiler in order to assess its efficiency and compare it with other available solutions. The results of this investigation will be crucial for the evaluation of the boiler concerned and will allow for a comparison with other devices available on the market. In addition, they will provide information on the use of filter technology based on metalworking waste, which can contribute to the identification of more sustainable solutions in the field of heating and emission reduction.

2. Materials and Methods

2.1. Characteristics of the Tested Automatic Pellet Boiler

Automatic pellet boilers are gaining popularity among owners of detached houses. They are attractive mainly because of their simple design and operation. Typically, they consist of a pellet tank and a heat exchanger with a burner, which are connected by means of a fuel feeding system. The most commonly used feeders are screw feeders which move the pellets into the combustion chamber by means of a spiral component. Alternatively, piston feeders are used, which feed a set amount of fuel with each movement of the piston. These are more flexible as they can handle different forms of fuel, such as pellets, granular coal and shredded straw or wood chips.

The laboratory measurements were taken at the Centre of Sustainable Development and Energy Saving AGH WGGiOŚ "Miekinia". The test was carried out on a boiler test bench and concerned a 25 kW ECONOMIC-BIO KOWA pellet boiler made by TREE Worker company, Biskupice Obłoczne, Poland. The boiler, shown in Figure 1, differs from other solutions available on the market by the presence of two flue gas filters. These filters are

made of metalworking waste enclosed in welded cartridges which are inserted into the chambers accessible through the side clean-out doors of the boiler. In Figure 1, the places of the filters' installation and the cross section of the boiler's heat exchanger are shown. The flue gas flow is horizontal in the first part of the heat exchanger, and then is vertical.

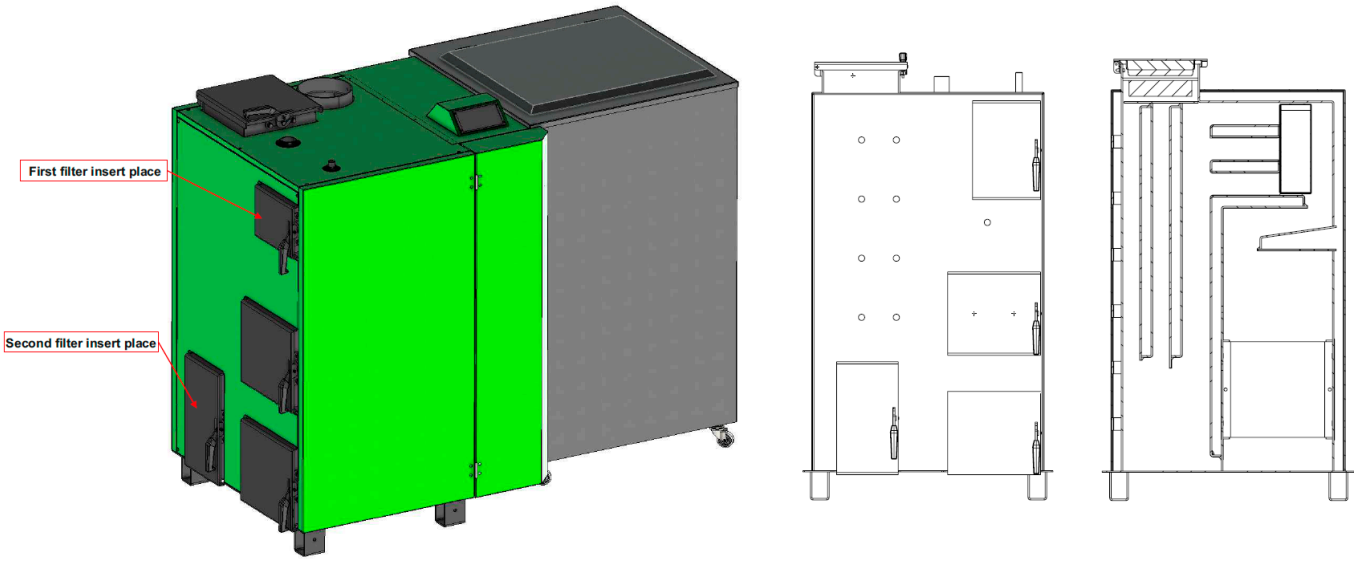


Figure 1. An illustrative representation of the pellet boiler under study with highlighted places with installed filters (**left**) and the cross section of the boiler's heat exchanger (**right**).

An additional characteristic of the boiler is the design of the burner, in which the secondary air supply can be adjusted by means of special shutters depending on the fuel being burnt. In the boiler a piston feeding system is used, which is less popular than the screw conveyor feeding system. However, the burner tested lacks an automatic ignition function (the model supplied for testing did not have an igniter). The detailed specifications of the tested boiler supplied by the manufacturer are shown in Table 1.

Table 1. Technical data of the boiler under test.

Parameter	Unit	Value
Designation of the boiler type and size	—	Economic-Bio 25
Rated thermal output	kW	25
Combustion's thermal efficiency	%	83.3
Inlet and outlet water parameters	°C	80/70
Permissible water temperature in the boiler		<95
Required flue draught	Pa	20
Water capacity	dm^3	100
Flue gas temperature: rated output minimum output	°C	 250 185
Flue gas mass flow: rated output minimum output	Kg/s	 0.02 0.006
Dimensions of the flue outlet spigot Dimensions of inlet and outlet pipe spigots	mm	150 40
Temperature setting range	°C	30–80

Table 1. *Cont.*

Parameter	Unit	Value
Fan speed setting range	%	10–100
Minimum return water temperature (at boiler inlet) Fuel type, moisture content and grain size	°C	40 <25
Fuel tank capacity	dm^3	350
Electrical power supply	V Hz	230 50
Electric power consumption—max	kW	0.23
Permissible water pressure in the boiler	bar	<1.9
Boiler's weight without water	kg	400
Boiler's overall dimensions (insulated water casing alone) length width height	mm	 830 1700 1200

The design of the water heat exchanger of the boiler allows for the installation of flue gas turbulators. Two flue gas turbulator inserts were used during the tests. The first has the dimensions (H × W × D) 0.13 m × 0.44 m × 0.1 m; the second has the dimensions (H × W × D) 0.33 m × 0.44 m × 0.1 m. One of the turbulator inserts using metalworking waste, i.e., machining shavings, is shown in Figure 2. The turbulator inserts are a low-cost solution for improving the efficiency and decreasing the dust emissions. The estimated costs of the fabrication of two such filters for a 25 kW boiler is 200 €. These costs are lower than 5% of the boiler cost. The effect of their use was investigated as part of this work.



Figure 2. The turbulator insert.

2.2. Description of Laboratory Testing Facility and Measuring Instruments Used

The tests were carried out using a testing facility for solid fuel boilers under laboratory conditions. This test rig consisted of a hydraulic and a flue system to which an automatic pellet boiler was attached (Figure 3). In Figure 3, in the foreground the real view of the automatic pellet boiler is shown, and in the background laboratory equipment is shown. In order to determine the composition of the exhaust gas, a Sensonic IR-1 gas analyser (made by Madur Polska Sp. z o.o., Zgierz, Poland), a MANOX-CLD (made by Madur Polska Sp. z o.o., Zgierz, Poland) nitrogen oxide analyser and a gravimetric dust meter were used.



Figure 3. The boiler attached to the test rig in the laboratory in Miękinia.

2.2.1. Sensonic IR-1 Analyser

The Sensonic IR-1 flue gas analyser (Figure 4) is an instrument designed for measurements of gas components, such as O_2, CO, CO_2, NO and NO_2. It is equipped with 2 non-dispersive infrared sensors (NDIRs). These sensors work on the principle of the absorption of infrared radiation at a given wavelength. The gas passes through the sensor and falls into a beam of infrared radiation of a particular wavelength. Part of the radiation, however, is absorbed by the gas passing through the detector so that the amount of radiation reaching the detector on the other side is reduced. Given that the degree of radiation absorption for a particular substance is characteristic of that substance at a given wavelength, the system can determine the content of the gas with a high degree of accuracy. In Figure 4, from left to right the gas drier, NO and NOx module and the main module of the Sensonic IR-1 device are shown.

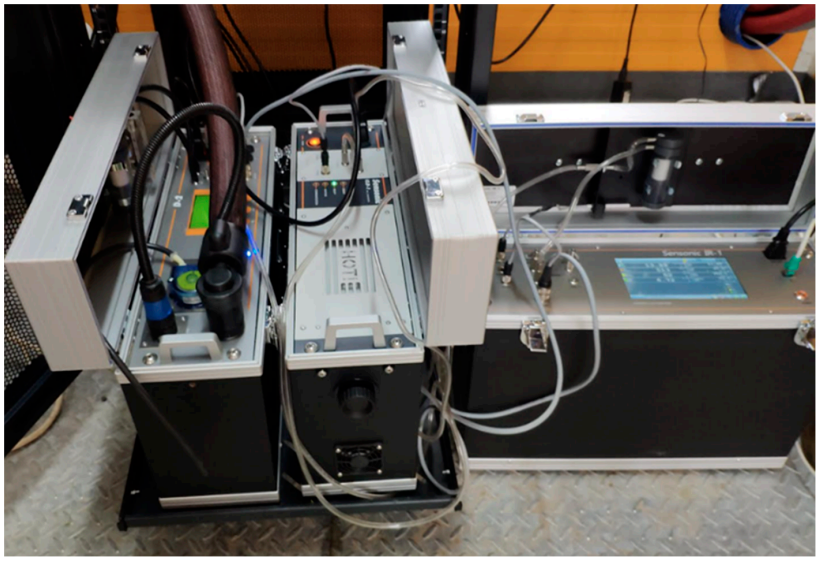


Figure 4. The Sensonic IR-1 flue gas analyser.

2.2.2. Dust Meter

The dust meter used for testing solid fuel boilers (Figure 5) at the laboratory in Miękinia uses the gravimetric method for operation. This method involves taking samples of the flowing gas containing solid particles and determining the mass of these solid particles relative to the volume of the flue gas. The results were determined as follows: first came the determination of the volumetric gas flow rate based on the measurement of the gas velocity. Next, when the gas flow rate was adjusted, a sample of the solids was collected on a quantitative filter paper. Thereafter, the volume of the gas sample was determined, and the solid fraction was weighed. Finally, the dust concentration in the flue gas was calculated. In Figure 5, it is shown that the dust meter consists of the flue gas probe with a place to install filter paper, the gas cooler, gas filters, gas meter and the vacuum pump.

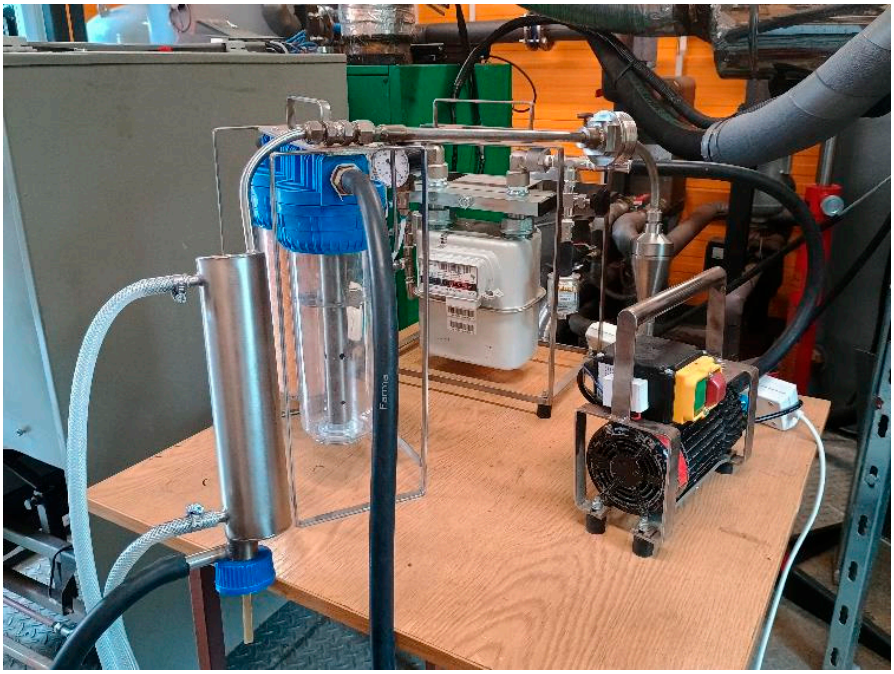


Figure 5. The dust meter used for testing solid fuel boilers.

The test procedure started with the probe being placed in the flue gas pipe. The gas was then sampled isokinetically for a pre-set period of time, i.e., 30 min. It was important that the gas was collected isokinetically, i.e., at the same speed and in the same direction as the main flue gas flow. This made it possible to avoid the aerodynamic separation effect and ensured an adequate distribution of the solid matter particles.

2.3. Method

The testing of the emissions and energy efficiency of the boiler was carried out for wood pellets. The characteristics of the pellets used for the tests are described in Table 2. The fuel used was an ENPlus A1-certified (Bioenergy Europe) pellet. The diameter of the wood pellets used was 6 mm, the bulk density was 660 kg/m^3, the calorific value was 4.99 kWh/kg, the ash content was 0.3% and the moisture content was 5.71%.

Table 2. Technical data of the pellets used in the testing (source: https://pellet4future.com/; accessed in 12 October 2023).

Parameter	Unit	Value
Certificate		ENPlus A1
Diameter	mm	6
Bulk density	kg/m^3	660
Calorific value [MJ/kg]	MJ/kg	17.98
Calorific value [kWh/kg]	kWh/kg	4.99
Ash content	%	0.3
Moisture content		5.71

Next, the Sensonic IR-1 and Manox-CLD flue gas analysers were prepared for testing. After starting the operation, the devices were warmed up and then flushed with a neutral gas. The analyser thus prepared could take continuous measurements of the flue gas. A dust meter was also prepared for dust extraction. The first step was to prepare the measuring probe. A pre-prepared filter paper was placed in the probe, which was then tightly capped. The preparation of the quantitative filter paper consisted of heating it in a laboratory oven at 250 °C, after which it was placed in a special glass vessel containing silica gel for 24 h. This was performed to get rid of any moisture from the filter. The filter thus prepared was weighed and placed in the measuring probe. A cooler was then attached to the probe together with a container for the moisture condensed from the flue gas. The cooler was then connected to the draught control device of the probe (the draught must be kept at the same level as the flue draught to ensure that the measurement is isokinetic), which consisted of a gas meter, a device responsible for measuring the draught in the apparatus and a vacuum pump. The draught value was controlled by means of two valves.

The first dust measurement was conducted between 12:34 and 13:04, after which the larger of the two filters was pulled out and the dust measurement was resumed (14:11–14:41). In the final step, the second, smaller filter was pulled out, which took place at around 14:50 h and was followed by the third final dust measurement (15:12–15:43 h). The filter papers after the dust measurement are shown in Figure 6. At the top left, there is the filter paper after the dust measurement without turbulator inserts installed in the boiler, on the right, the filter paper without the bigger turbulator and at the centre bottom, the filter paper with two turbulators installed in the boiler.

At 15:50 h, the shutdown of the boiler was started. The test results used for the analysis were taken from a four-hour period (between 11:50 h and 15:50 h).

The data were automatically recorded by the test rig control software. The data readings were then tabulated, and the instantaneous heat output of the boiler was computed for each reading. Formula (1) was used for this purpose.

$$P_n = m_w \cdot c_w \cdot (t_z - t_p) \quad (1)$$

where

- P_n—instantaneous heat output [kW];
- m_w—mass flow rate of the water $\left[\frac{\text{kg}}{\text{s}}\right]$;
- c_w—specific heat of the water in the temperature range (t_z, t_p) $\left[\frac{\text{kJ}}{\text{kg}\cdot\text{K}}\right]$;
- t_z, t_p—instantaneous flow and return temperatures [°C].

The useful efficiency of the boiler was then calculated according to Formula (2).

$$\eta_n = \frac{P_n}{P_d} \cdot 100\% \quad (2)$$

where

- η_n—useful efficiency [%];

- P_d—heat input in the fuel (burner heat input) [kW].

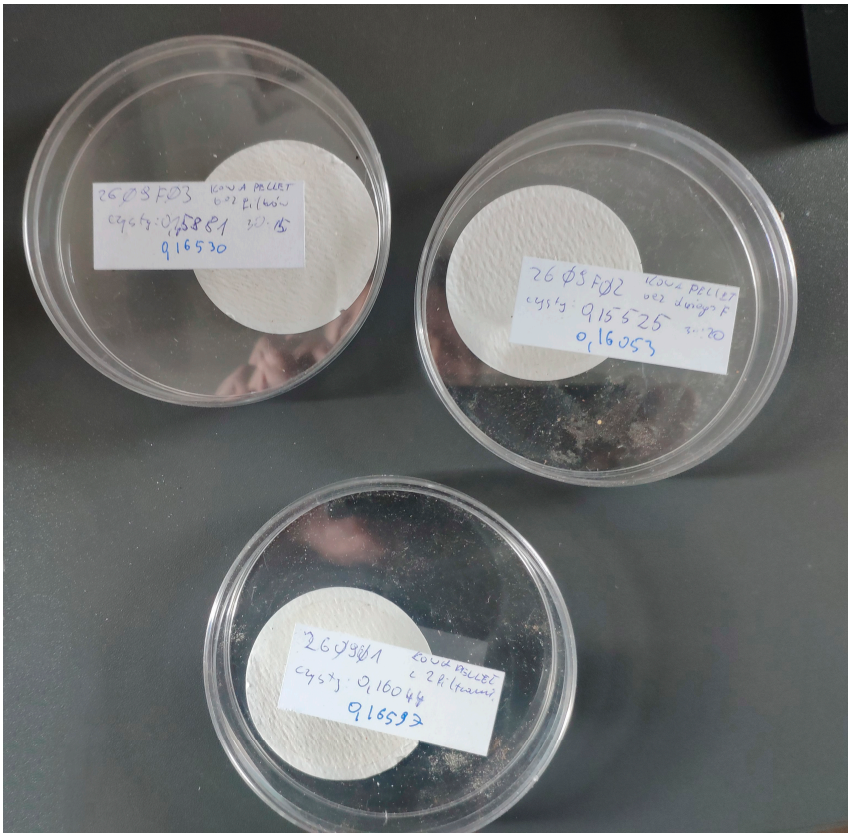


Figure 6. Filter papers after the dust measurement process.

3. Results and Discussion

The test results (apart from the dust concentration in the flue gas) were continuously recorded using the software installed in the system.

3.1. Analysis of Test Results

Based on the temperatures and water volumetric flow rates recorded, the heat output of the boiler was calculated (Figure 7). In the first phase, a steady increase in the flow and return temperatures can be seen, which indicates that the process of stabilising combustion was proceeding correctly. The stabilisation of the test rig was completed at 11:50 h. It can be seen that despite the occurrence of some temporary disturbances in the readings, the heating power and the flow and return temperatures were relatively stable from this point until the shutdown of the boiler was started. The average heat output during the actual test (11:50–15:50 h) was 26.86 kW, while the average flow and return temperatures were 76.38 and 63.55 °C, respectively.

During the actual tests, 24 kg of pellets were burned. With these data and using the methodology previously referred to, it was calculated that the average efficiency of the boiler during the entire test was 89.7%. The efficiency of the boiler in the case of operation without turbulators was 83.65%; the efficiency of the boiler with a single turbulator was 87.53% and was 95.58% with two turbulators. The average electrical power consumption in the operation mode was 0.11 kW and was 0.006 kW in standby mode. All boiler energy parameters are summarised in Table 3.

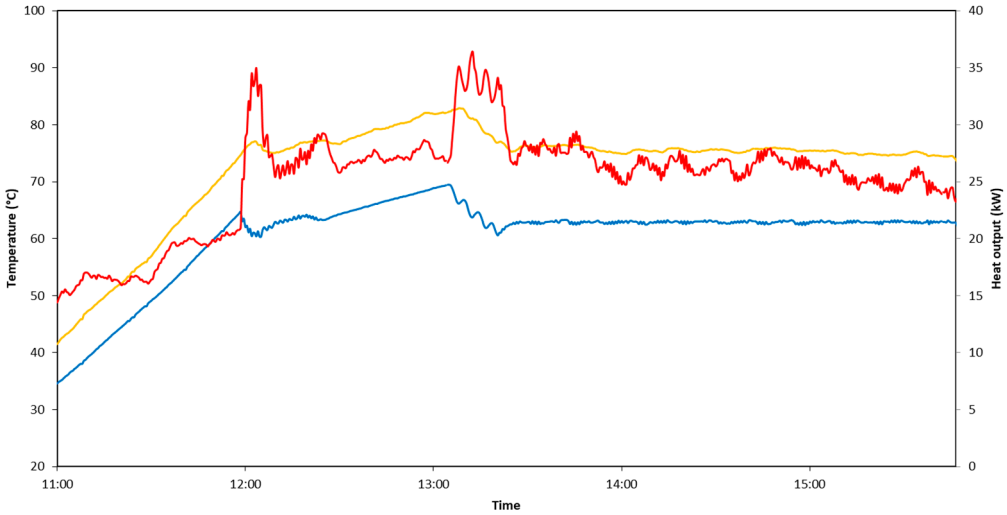


Figure 7. Flow temperature, return temperature read from the system and calculated heating output.

Table 3. Energy performance of the boiler under test.

Parameter	Value
Average heat output [kW]	26.86
Energy efficiency ratio [%]	129.56
Boiler efficiency with both filters fitted [%]	95.58
Boiler efficiency with one filter fitted [%]	87.53
Boiler efficiency without filters [%]	83.65
Power consumption at rated heat output [kW]	0.11
Power consumption in standby mode [kW]	0.006

Throughout the testing, oxygen and carbon dioxide values were continuously monitored (Figure 8). The concentrations of these substances in the flue gas are indicative of the quality of the combustion process, which can therefore be monitored. They also indicate the time of completion of the process of stabilising combustion. The oxygen concentration should be in the range of 6–9% and the carbon dioxide concentration in the range of 5–8%. When analysing Figure 8, it can be seen that in the initial phase of the testing the oxygen values reached 21%, i.e., the amount of oxygen in the atmospheric air, which meant that combustion was not taking place at that time. The start of the combustion process can be determined as the moment when carbon dioxide appears in the flue gas. It was assumed that the moment of stabilisation is the moment when the concentration of oxygen and carbon dioxide reach stable values within the previously given ranges. Momentary peaks occurred in the concentration values (oxygen up to 21% and carbon dioxide up to 0%) which are associated with the opening of the clean-out door to put in or remove turbulator inserts. The first peak took place around 13:10 h, when the bigger turbulator had been uninstalled, and then the second peak took place around 14:50 h, when the smaller turbulator had been uninstalled. The average value of the oxygen concentration in the flue gas during the tests was 9.25%, which corresponds to an oxygen excess coefficient λ of 1.79.

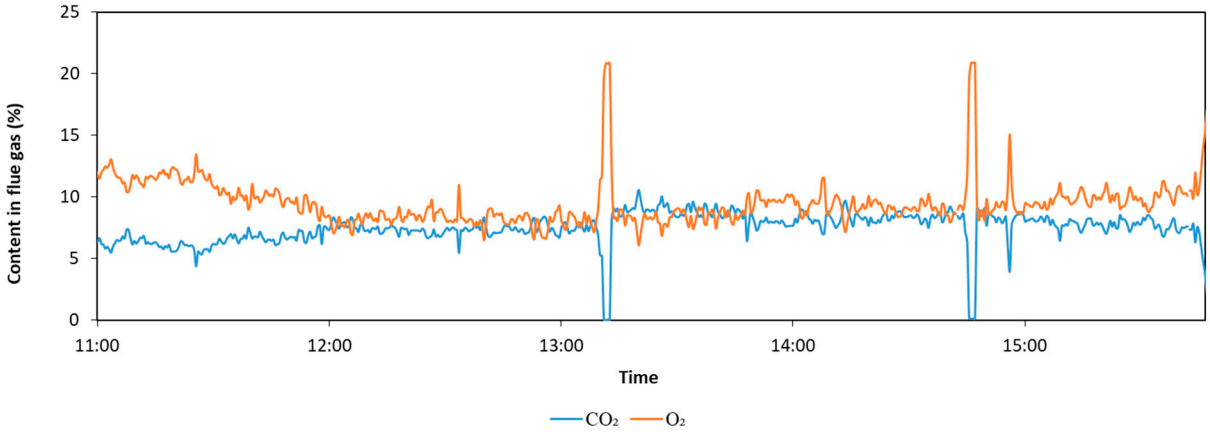


Figure 8. Oxygen and carbon dioxide contents of the flue gas during the test.

Carbon monoxide and nitrogen oxide concentrations were also recorded (mg/m^3 at 10% oxygen content in the exhaust gas and under standard pressure and temperature conditions), as shown in Figure 9. The average nitrogen oxide content in the exhaust gas during the test was 187.66 mg/m^3 and the average carbon monoxide content was 22.7 mg/m^3. Similarly, as shown in Figure 8, here also sudden fluctuations in the concentration values (the NO_x concentration is rising and the CO concentration is going to 0) are seen, which are associated with the opening of the clean-out door to put in or remove turbulator inserts.

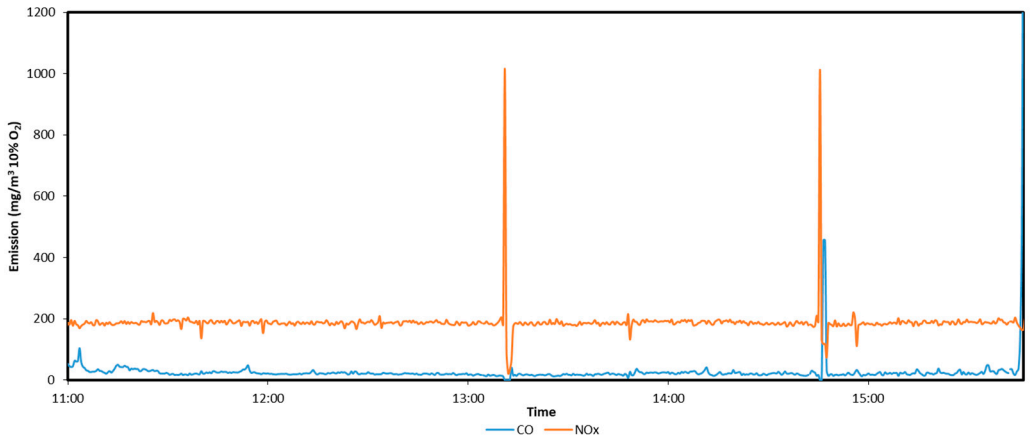


Figure 9. The contents of carbon monoxide and nitrogen oxides in the flue gas expressed in terms of mg/m^3 at 10% oxygen content in the flue gas and under standard conditions of pressure and temperature.

The determination of the dust content showed that the dust content during the individual tests was 21.08 mg/m^3 at 10% oxygen (with both turbulators installed), 21.98 mg/m^3 at 10% oxygen (with only the larger turbulator installed) and 29.72 mg/m^3 at 10% oxygen (when neither of the turbulators was installed).

These results can be directly compared with the maximum permissible emissions for boilers meeting the requirements of Class 5 according to PN-EN 303-5:2021 [54]. All the environmental parameters of the boiler are summarised in Table 4.

Table 4. Values of the seasonal emission parameters of the boiler under test.

Parameter	Value
CO_2 emissions [mg/m^3] 10% O_2	22.7
NO_x emissions [mg/m^3] 10% O_2	187.6
Dust emissions [mg/m^3] 10% O_2 for two turbulators	21.08
Dust emissions [mg/m^3] 10% O_2 for one turbulator	21.98
Dust emissions [mg/m^3] 10% O_2 without turbulators	29.72

3.2. Evaluation of the Parameters of the Boiler Under Test

The test results for the boiler were further compared with the requirements of the PN-EN 303-5:2021 standard for Class 5 boilers. Only such boilers may currently be distributed in the Polish market. Table 5 summarises the parameters required for Class 5 according to PN-EN 303-5:2021 and those obtained for the boiler during the tests.

Table 5. Boiler performance compared with the requirements of PN-EN 303-5:2021.

Emission Requirements for Solid Fuel Boilers	Parameter	Unit	Requirements	Values Determined
Class 5 acc. to PN-EN 303-5:2021	Boiler efficiency	%	≥88.4	89.7
	Pollutant emissions			
	Carbon monoxide	[mg/m^3]	≤500	22.7
	Dust	[mg/m^3]	≤40	21.08

When analysing these values, it can be concluded that the boiler efficiency determined during the tests is higher than the minimum required for this type of boiler; additionally, the carbon monoxide emissions are more than 20 times lower than the maximum value while the average dust emissions (for the three different configurations regarding the use of turbulators) are almost twice lower than the maximum allowed for Class 5.

An analysis of the utilisation of turbulator inserts in the boiler, which contain metal-working waste, further reveals the extent of their positive impact on the boiler operation (Figure 10). After fitting both turbulators, the heat output increases by 14.25%, which significantly affects the amount of heat supplied by the boiler. This also translates into the boiler efficiency, which reaches 95.6% with both turbulators in place, i.e., 11.9% higher than without the turbulators. The situation with environmental parameters is similar, where particulate emissions fall by 29.1%. A positive effect can also be seen for CO emissions. When the boiler is operated with both turbulators, it produces 3.05 mg/m^3 less carbon monoxide compared with when no additional components are fitted. The only parameters that are not affected by the presence of the filters are nitrogen oxide emissions. Here, no significant changes in emissions were observed regardless of the number of turbulators fitted. It can therefore be noted that these components have a significant effect on improving heat absorption in the water jacket as well as reducing the amount of particulate matter emitted by the boiler in the flue gas.

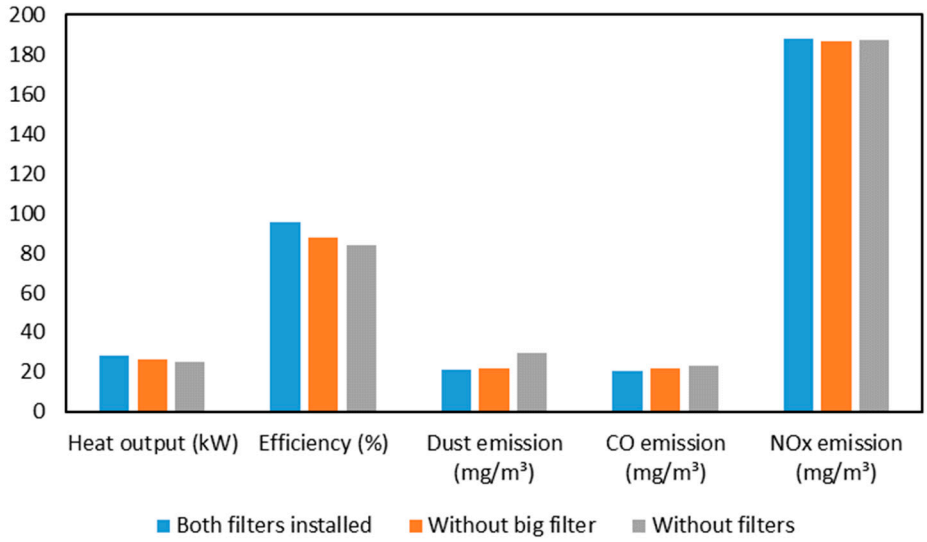


Figure 10. Summary of the values of the energy and emission parameters of the boiler for different configurations of the turbulator inserts.

4. Conclusions and Remarks

During the tests and analyses carried out on the Economic-Bio boiler by Kowa, the strengths and weaknesses of the device were defined. Energy and emission parameters were computed and the results showed that the boiler meets the requirements of Class 5 according to the PN-EN 303-5:2021 standard.

The aim of the investigation was to determine the energy and emission parameters of the selected boiler in order to assess it in terms of its energy and emission performance. The most important energy parameters, i.e., the heat output and thermal efficiency, reach values of 26.86 kW and 87.97%, respectively. These results demonstrate the high potential of the boiler. The emission parameters are also extremely promising. The averaged carbon monoxide emissions are 22.71 mg/m^3. This is extremely low for this type of boiler. Nitrogen oxide emissions are 187.6 mg/m^3. With regard to particulate emissions, the values for the different turbulator variants are as follows: 21.08 mg/m^3 (dust emissions with both turbulators in place), 21.98 mg/m^3 (dust emissions with one, the larger turbulator, in place) and 29.72 mg/m^3 (dust emissions without any turbulators fitted). A good deal of information was also obtained on the technology of turbulator inserts using metalworking waste and on the effect they have on the boiler operation. It has been shown that there was a significant increase in the heat output (3.57 kW) and boiler efficiency (11.93%) as well as a marked decrease in dust emissions (40.9%). It has also been shown that these turbulators are a very promising technology that may prove viable for wider implementation. The low cost of fabrication, which is lower than 5% of the boiler's price, makes this technology promising for implementation.

However, the investigation is subject to inaccuracies that could be addressed by extending the scope of the study. First and foremost, it is proposed to carry out trials with permanently installed filters as under such conditions the boiler will achieve the most favourable performance values due to a stable combustion process without allowing in additional air. An additional study of the effects of turbulators is also proposed as this technology has shown very good results in terms of positive effects on the emission values and energy performance values of the boiler.

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A.N. and W.K.; project administration, A.J.; funding acquisition, A.N., A.J. and G.P. All authors have read and agreed to the published version of the manuscript.

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