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Comparison of Emissions and Efficiency of Two Types of Burners When Burning Wood Pellets from Different Suppliers

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Abstract: Wood pellets play an important role among biomass materials used as fuel. At the same time, today's economic, environmental, political and social realities, as well as other circumstances related to fuels used for heat generation, mean that there is demand for increasingly efficient and environmentally friendly combustion sources. As is well known, each combustion source has a different efficiency due to its intended use, design, principle of operation and the type and composition of the fuel burned. The amount of pollutants emitted into the environment during combustion also largely depends on these factors. The aim of this study was to compare the flue gas emissions and efficiency of two pellet burners of different design, burning certified A1 wood pellets from different suppliers. The emission requirements were met during the combustion of wood pellets in a boiler with the two burners tested (one with a moving grate and an overfed burner). The analyses and studies carried out aim to improve the capability of managing the efficiency and environmental performance of the heat source (i.e., a boiler or a burner) and the fuel (type of wood pellets). This is done in the context of demonstrating a better combustion source when selecting the right burner and fuel in terms of efficiency and emissions. In this paper, comparisons of flue gas emissions are presented along with characteristics in the form of graphs, as well as thermal and combustion efficiencies for the corresponding solid fuel used in the form of wood pellets. After comparing the emissions, it was found that the statistical averages of CO, NOx, dust and VOCs were similar for combustion at full power using the burners tested. Taking into account the pollution levels at combustion, it can be said that the difference in CO emissions at full and minimum combustion is lower for the experimental burner compared with the moving grate burner (reference burner). In summary, it can be concluded that the experimental overfed burner under consideration can be successfully used as a solid fuel boiler to burn wood pellets.

Keywords: wood pellets combustion; wood pellets; emissions; combustion efficiency; efficiency of pellet boiler; pellet burners

1. Introduction

Reducing the use of fossil fuels is a key challenge of the modern world. This is also important because it is estimated that by 2050, only about 14% of proven oil reserves, 72% of proven coal reserves and 18% of proven gas reserves will remain [1]. This reduction is extremely difficult because continued population growth also brings with it an increase in the consumption of energy and natural resource, thus counteracting the improvement of energy efficiency measures and the continued growth of the renewable energy industry [2–4]. At the European Union level, a new development strategy, the 'Green Deal', was adopted in 2019 to achieve climate neutrality by 2050 [5]. In this strategy, great importance is given to increasing the use of renewable energy and improving energy efficiency [6]. The Commission proposes to increase the binding target for renewables in the EU energy mix to 40%. Furthermore, the Commission wants to achieve an overall 36–39% reduction in final and primary energy consumption by 2030 [7]. The use of biomass is one of the keys to achieving climate neutrality in 2050, as well as in global energy demand projections [8].

Energy from biomass is one of the main sources of renewable energy in the EU. According to Eurostat data [9], the share of renewables in gross final energy consumption was 22.1% in 2020. In turn, in 2020, the share of biomass energy in RES was 57.1% [10]. It has been demonstrated that biomass is an energy source capable of meeting the growing demand for clean energy sources that can last for a long time [11]. Furthermore, among renewable energy sources, biomass is one of the least dependent on prevailing weather conditions (unlike photovoltaics or wind turbines); at the same time, it does not require substantial investments (unlike hydropower, geothermal or wind energy). According to some studies, the availability of forest biomass in Europe from a mapped area of 10 km $\times$ 10 km is between 357 and 551 Tg of dry matter per year [12]. Furthermore, biomass is a low-emission energy carrier in terms of carbon dioxide (CO_2). Therefore, the CO_2 balance of biomass in the atmosphere is at zero, according to the assumptions of the Paris Agreement on the planning to reduce carbon dioxide (CO_2) emissions through the increased use of biomass for energy [13–15]. Pellets are the most convenient of the biomass solid fuels available. They are characterised by a higher energy density than wood chips, which means that the requirements for transport and storage capacity are lower. Compared with non-densified biomass, pellets are characterised by lower moisture content, higher calorific value, uniform shape, pronounced combustion and reduced ash [16–22]. Recent geopolitical developments have caused significant market disruption both in terms of price and supply. Nevertheless, wood pellets remain competitive as compared to almost all other energy sources and could become even more attractive with a series of targeted measures (e.g., VAT reductions, in line with what applies to other energy sources) [23]. The increase in prices and limitations in the supply of pellets may be factors limiting their practical use as fuel.

The current political and economic situation in the world causes a reduction in the supply of hydrocarbons (coal, oil and gas), especially in the European market. As a result, individual buyers in Poland are experiencing problems with purchasing good-quality coal to heat their homes. In addition, this fuel is very expensive. Moreover, the tense situation in the world due to, inter alia, the war in Ukraine, causes great uncertainty as to the future supply of hydrocarbons. All these indications point to the need for an increasing share of good quality wood pellet boilers in the Polish heating market.

This is important, especially because coal combustion remains one of the main sources of household heating, being the most common energy carrier in the Polish countryside [24,25]. In 2018, solid fuels (hard coal and firewood) were used in 45.4% of households in Poland. The use of hard coal for heating occurs to the greatest extent in the Polish countryside. As of 2018, as many as 71.3% of detached houses in rural areas used coal for heating, compared with 20.0% in urban areas [26].

The Energy Policy of Poland until 2040 assumes that the use of biomass, both thermal and anaerobic in biogas plants and for the production of liquid biofuels, will increase. It is important to use biomass as close to the place of its production as possible [27]. The document presents a projection of a 62% increase in biomass production in 2040 compared with 2015 using mainly domestic potential. Demand for biomass will increase in all sectors. Along with the increase in prices of CO_2 emission allowances, the profitability of biomass use will increase in the electricity and district heating sectors. In households and services, greater use of biomass than so far will involve replacing old coal-fired boilers with modern pellet-fired ones [27]. This is the most efficient and cleanest use of biomass for domestic heating.

In 2018, Poland launched the 'Clean Air' programme, the main objectives of which are to improve the energy efficiency of buildings and reduce emissions of dust and other pollutants into the atmosphere, mainly from the heating systems in detached houses which not infrequently still use old, low-efficiency solid fuel boilers that also burn low-quality fuel [28–30]. Changing the structure of consumption of energy carriers by replacing fossil fuels with energy from renewable sources may result in savings of fossil energy carriers, as well as a reduction in the emissions of pollutants to the atmosphere, resulting in improvement of air quality [4,31,32]. As of 2019, Poland used approximately 70.4% of all solid fossil fuels consumed for domestic heating in the European Union in [33]. Over the past 10 years, there has been a gradual decline in the use of coal-fired boilers [34].

Particulate matter pollution in Poland is mainly caused by low stack emissions (emissions from chimneys less than 40 m high) from household heating [35–37]. This is a very important argument for replacing outdated solid fuel boilers with environmentally friendly energy sources. Pellet boilers are a good solution in this respect. The phasing out of coal and oil boilers and, in a further phase of decarbonisation, also of gas boilers, creates a market potential for biomass heating appliances (in particular, pellet boilers). The greatest such potential exists in Poland, Ireland, Belgium, Italy, Germany and the Netherlands [38]. Compared with wood boilers, pellet boilers have automatic feeders, automatic cleaning systems and automatic ignition systems.

Pellet boilers are becoming increasingly popular on the Polish heating market. They are mostly replacing the older generation of omni-fuel boilers, which are very inefficient especially when burning wood logs [39]. The share of biomass boilers in total solid fuel boilers sold in 2018 was 35–40% and had already reached 80% by 2020 [34]. The share of biomass boilers in the total Polish market for household heating appliances between 2014 and 2019 was 20% [40]. Pellet boilers are the appliances that produce the lowest emissions of air pollutants compared with other solid fuel boilers [39]. However, the problem of emissions in the flue gas cannot be completely eliminated [41–43]. All currently available pellet boilers are class 5 according to the PN-EN 303-5:2012 standard [44] and comply with the Ecodesign requirements [45]. The minimum thermal efficiency of a 20 kW pellet boiler in class 5 is 88%. According to the PN-EN 303-5:2012 [46] standard, the maximum CO emissions for automatic biomass boilers are 500 mg$\cdot$m^{-3}, the maximum emissions of organic gaseous compounds (OGCs) are 20 mg$\cdot$m^{-3} and the maximum emissions of dust are 40 mg$\cdot$m^{-3} (each value was converted to 10% oxygen concentration in the flue gas). These boilers also meet the requirements of the Ecodesign Directive [47] and are in energy efficiency class A+ according to the Commission Delegated Regulation (EU) No 811/2013 [48].

In Poland, not all manufacturers currently comply with the relevant standards for the quality of pellets placed on the market. Pellet producers are highly dispersed, and many of them depend on the amount of sawdust and wood chips generated in their core business of sawmilling. If the market conditions are tough for sawmill products, then the supply of wood pellets decreases. Only the largest manufacturers, with a daily production of over 24 tonnes, opt for certification. The most popular is the ENplus certification. This certificate is a pan-European standard for wood pellets based on the quality requirements of EN ISO 17225-2 (with three classes of wood pellets A1, A2 and B, where class A1 is the best-quality pellet). The scope of certification includes pellet parameters regarding pellet dimensions, ash and trace element content, mechanical resistance and calorific value. There is a national certificate provided for small-scale producers which guarantees product compliance with EN ISO 17225-2 but is not recognised in other countries. It enables them to sell wood pellets locally at a price lower than the European average, which increased from about 25 euro-cent$\cdot$kg^{-1} in 2020–2021 to about 65 euro-cent$\cdot$kg^{-1} in November 2022 [49]. At a time of Poland's energy transition and a shift away from fossil fuels, particularly coal and lignite, the stable and affordable price of wood pellets offers Poland a chance to remain on the decarbonisation pathway adopted in its commitments to the EU Commission and to ensure the security of fuel supply to the household and municipal sector where coal played such a role for decades.

The aim of this study was to compare the flue gas emissions and efficiency of two pellet burners of different design, burning certified A1 wood pellets from different suppliers. The analyses and studies carried out increase the capability of managing the efficiency and environmental performance of the heat source (i.e., a boiler or a burner) and the fuel (type of wood pellets). This is done in the context of demonstrating a better combustion source when selecting the right burner and fuel in terms of efficiency and emissions.

2. Materials and Methods

In order to carry out the tests, we used a 16 kW boiler with automatic fuel feeding designed for burning wood pellets. The appliance in question belongs to a series of low-temperature steel boilers designed for open and closed systems. In the boiler, the air flow into the combustion chamber is supplied by a blower fan. The operation of the individual boiler components is supervised by a controller with specialised software. The boiler has a vertical flue gas flow through two-pass fire tube heat exchangers with spring turbulators (flue gas swirlers) in each tube. This design makes it possible for the boiler to achieve a high level of efficiency, Figure 1. Due to the nature of the testing and the fact that a heat exchanger that was not thermally insulated was used as a prototype, heat loss to the environment was noticeable.

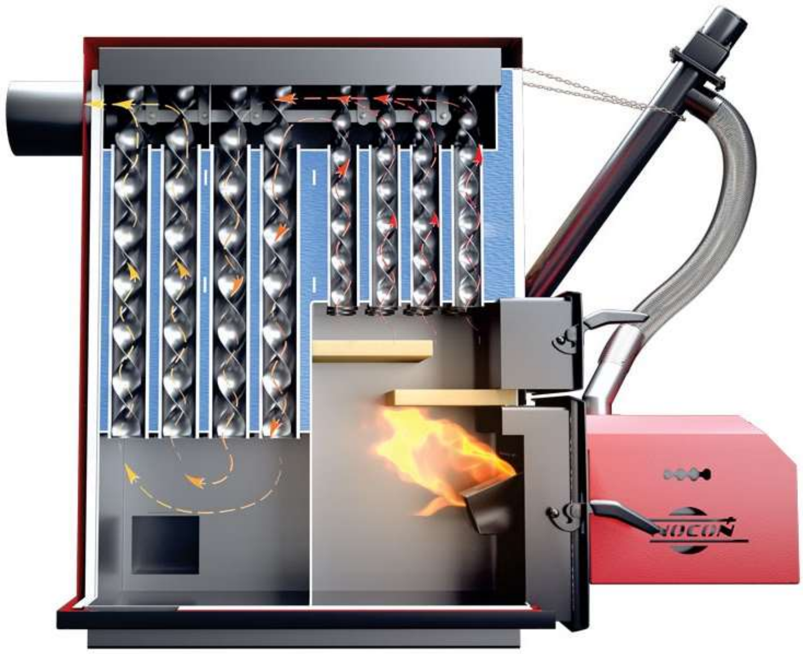


Figure 1. Cross section of the solid fuel boiler tested [50].

This paper compares the effects of the combustion process for two pellet burners of different designs and three brands of commercially available wood pellets. The aim was to check the effect of the wood pellets being combusted on the emissions for a boiler meeting class 5 requirements, as well as to determine what emission effects can be achieved using burners of different designs. The first of the burners tested was a moving grate burner, characterised and described in the article [51]. This pellet burner is very popular on the market in Poland. As shown, it is also suitable for operation with agro pellets, such as miscanthus grass pellets.

The effects of the operation of the abovementioned burner with a horizontally fed burner and a moving grate were compared with those of an overfed burner. The overfed burner (Figure 2) is characterised by the cyclic feeding of pellets from above (dropping them in) so that they fall onto the grate by gravity. The grate in this appliance is in the form of a movable drawer. Upon completion of the operation in the heating mode, or at specified intervals, ash removal from the burner is carried out by pulling the grate out, which results in the ash falling into the ash pan drawer. An automatic control system ensures that the fuel is fully combusted on the grate before the grate is opened, and then the ash naturally falls into the ash pan. Table 1 shows the comparison of the technical specifications of both tested burners.

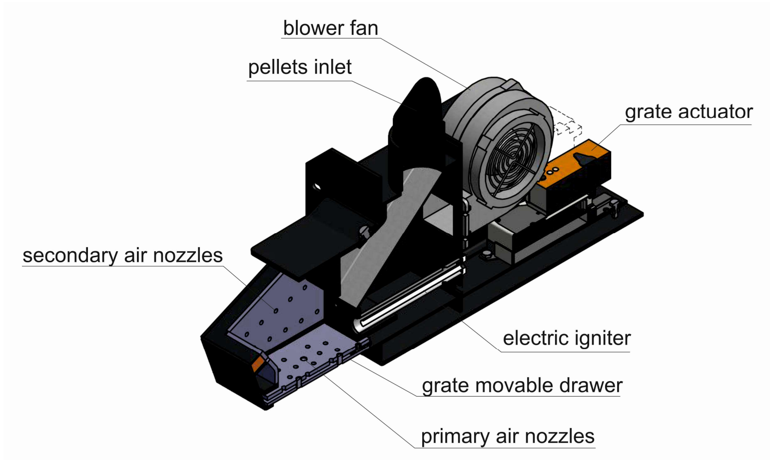


Figure 2. A 16 kW experimental overfed burner which was used for testing [52].

Table 1. Comparison of the technical specifications of tested pellet burners.

Parameter	Moving Grate Burner	Experimental Burner
Feeding system	horizontally with stoker	over-fed (gravity)
Ash removing system	moving grate (deashing possible during working stage)	movable drawer (deashing possible extinguishing mode)
Firing-up	Electric heater	Electric heater
Air supply system	blower fan with speed modulation (the air stream is divided for primary and secondary stream)	blower fan with speed modulation (the air stream is divided for primary and secondary stream)
Fire check-up system	photodiode	photodiode

Both burners tested had a ceramic igniter and an air supply fan. Air was supplied to both burners in the form of a primary and secondary flow.

In the first stage of testing, a pellet burner with a moving grate (Uni-Max; the reference burner) was installed in the boiler. The fuel was supplied from a hopper by means of a shaftless screw conveyor from the bottom of the hopper to the top, from where the fuel slid by gravity through the backflow preventer into the stoker chamber. Then, the stoker transported the pellets onto the grate.

Next, the experimental burner was installed. In this solution, a fan draws in ambient air (air form the room where the boiler is installed) and blows it into the air chamber of the burner. From the air chamber, the air is then supplied to the fuel through some nozzles located in the burner, and the fuel combustion process takes place. The fuel in the form of wood pellets is transported from the hopper in the same way as for the reference burner. In the case of an overfed burner, the pellets fell directly onto the hearth.

Regulation of the boiler heat output was carried out automatically by an electronic temperature controller. This controller controlled the operation of the feeder, blower, circulation pump, domestic hot water circulation pump, igniter and ash removal system. The following operation stages occurred for both burners tested:

- Ignition—At this stage, the fan first removed the ash from the grate after annealing of the char from the previous operating cycle. The initial dose of pellets was then fed onto the grate, and the electric igniter and fan were started. During this stage, the pellets heated up on the grate to the ignition temperature. The igniter operated until a flame appeared and was detected by a photocell installed in the burner. When the flame appeared, the boiler switched to heating mode.

- Operation—During fuel combustion on the grate, the fan operated continuously, and the fuel was cyclically fed in small doses. At this stage, the fan, screw conveyors (in both cases, the screw conveyor installed in the hopper is in operation, and the reference burner had an additional feeder, i.e., a stoker) and ash removal system were all in operation. For the reference burner, the ash removal system operated cyclically during burner operation at intervals of several minutes. For the test burner, the ash removal system operated at longer intervals (before the ash is removed from the grate, the fuel residue must burn out). With the controller used, both burners could operate at three power levels. For each of these levels, the burner manufacturer has implemented appropriate settings for the fuel feeding time, fan output and grate ash removal frequency.
- Shutting down—At this stage, the fan was in operation to provide air for full combustion of the pellets on the grate. For the reference burner, the moving grate system was also activated to transfer ash to the ash pan. For the experimental burner, the grate drawer was opened only after the pellets were fully burned out.

The comparative study of the burners and wood pellets was carried out at a solid fuel boiler testing facility located at the Centre of Sustainable Development and Energy Saving AGH WGGiOŚ 'Miekinia'. The testing equipment consisted of:

- A heating loop for the stabilization of temperature in the boiler and measures water flow, inlet and outlet temperature and pressure. The was installed for the electromagnetic flow meter, and for the inlet and outlet temperature, the measurements were user temperature transducers with PT100 sensors;
- A flue gas draft stabilization system with a draft fan and draft sensor;
- The flue gas analysing system with analysers Sensonic IR-1 and Sensonic MANOX-CLD, which continuously monitored O_2, CO, CO_2 and NOx in the flue gas. For the O_2 measurement, a para-magnetic sensor was used; for CO and CO_2, user NDIR sensors were used; and for NOx, the CLD method was used. For VOCs measurement, an instrument was used with the FID method, which was produced by LAT company. Dust in the flue gas was measured using a Testo 380 fine particle analyser (with measuring ranging from 0 to 300 $mg{\cdot}m^{-3}$ and a measurement uncertainty of 40%);
- A platform scale for pellet weighting with the range 0–60 kg, with resolution 20 g;
- The SCADA PROCES2 system was used to set the test parameters (the flow, outlet temperature, flue gas draft) and read and record data from analysers and sensors [51].

Thermal efficiency was calculated using Formula (1):

$$\eta_{th} = \frac{P}{B{\cdot}NCW}\ [\%] \quad (1)$$

where

P—heating capacity of the boiler (kW), calculated according to Formula (2);
B—fuel consumption rate ($kg{\cdot}h^{-1}$);
NCW—net calorific value of fuel ($kWh{\cdot}kg^{-1}$).

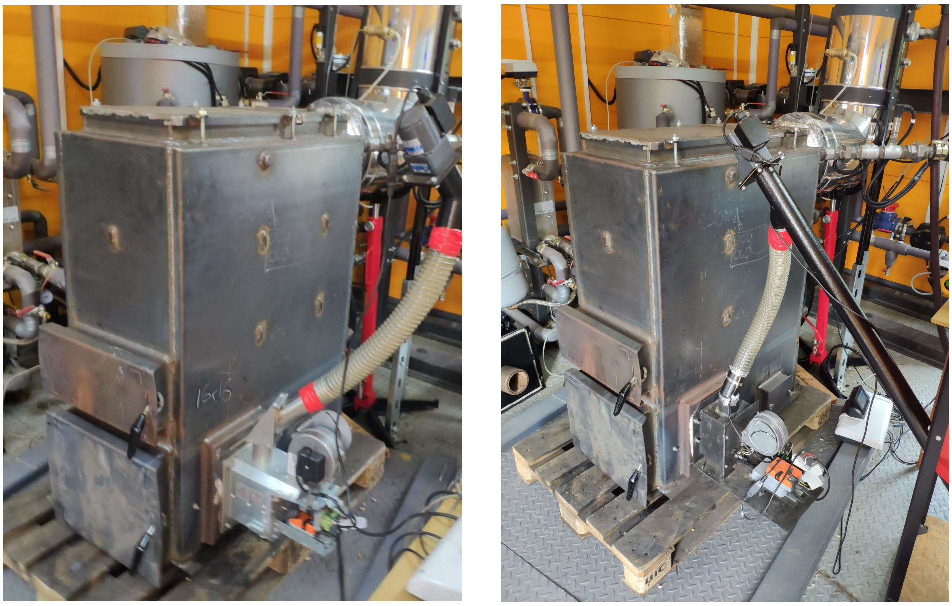
$$P = \frac{v{\cdot}\rho{\cdot}(T_2{\cdot}T_1){\cdot}c_w}{3600}\ [kW] \quad (2)$$

where

V—volumetric flow rate ($l{\cdot}h^{-1}$);
ρ—water density ($kg{\cdot}l^{-1}$);
T_2—boiler outlet temperature (°C);

T_1—boiler inlet temperature (°C);
c_w—water specific heat capacity (kJ· (kg·K)$^{-1}$).

The thermal efficiency of the boiler was measured for a thermally uninsulated heat exchanger (Figure 3), so it can only be used for illustrative purposes. Actual thermal efficiencies for pellet boilers can be as high as 90%. Combustion efficiencies were also compared for the individual fuels and burners.



(**A**) (**B**)

Figure 3. Tested boiler with the moving grate burner (**A**) and with the experimental burner (**B**) on the testing stand.

The combustion efficiency was calculated using Formula (3) [53]:

$$\eta_c = 100 - qA\ [\%] \quad (3)$$

where
qA—stack loss [45] calculated according to Formula (4) (%).

$$qA = (T_{gas} - T_{amb}) * (\frac{A_1}{CO_2} + B)[\%] \quad (4)$$

where
T_{gas}—flue gas temperature (°C);
T_{amb}—boiler inlet air temperature (ambient temperature) (°C);
CO_2—carbon dioxide concentration in flue gas (%);
A_1, B—Siegert's coefficients characteristic of pellets (dry wood), A_1 = 0.65, B = 0.

Each measurement for all the types of the wood pellets in the test was started by stabilising the boiler inlet and outlet water temperatures. The feeding and break parameters for the pellet feeders were then set in the controller. Setting these parameters was important in order to achieve the assumed heating output, regardless of the size and bulk density of the pellets tested. The boiler was assumed to operate at a nominal output of approximately 16 kW and a minimum output of approximately 4.8 kW (with the experimental burner installed), which was 30% of the nominal output. It was also necessary to adjust the fan capacity to ensure the correct supply of primary and secondary air to the burner. Each test was assumed to last 60 min. To calculate the fuel consumption rate, each pellet was weighted at scale before the test, and after test, the rest of pellet was weighted from fuel hopper; the difference (for 60 min of boiler operating) provided the fuel consumption rate.

The tests were carried out for certified class A1 wood pellets produced in accordance with the requirements of EN ISO 17225-2, acquired from three different producers. The fuel tested is widely available to individual customers on the domestic, i.e., Polish market. The fuel was delivered and stored in its original commercial packaging. For the purpose of this article, the pellets were described as A, B and C. Pellets A are produced from the sawdust of coniferous wood, mainly pine, larch, fir and spruce. The wood is first debarked so the feedstock used in the production does not contain any bark (Figure 4). In the production of pellets B, only conifer sawdust is used. The wood is also debarked prior to the production process (Figure 5). The last fuel used was pellets C. This fuel also uses pre-barked, dry conifer sawdust (Figure 6).

Figure 4. Wood pellets A.

Figure 5. Wood pellets B.

Figure 6. Wood pellets C.

3. Results and Discussion

Net calorific values for each type of tested pellets were calculated based on gross calorific values measured in bomb calorimeter KL-11. The highest net calorific value was 17.53 MJ·kg^{-1} for pellets C and the lowest, at 17.21 MJ·kg^{-1}, was found for pellets B. Pellets A and pellets B had similar moisture contents of 8.2% and 8.4%, respectively. Pellets C had a slightly lower moisture content (7.5%). Pellets C had the lowest ash content (0.31%), pellets B had a higher content (0.41%) and pellets A had the highest ash content (0.53%). As for the volatile matter content, it was approximately 85% for all the pellets tested. The volatile matter content values were 84.72% for pellets A, 85.14% for pellets B and 85.87% for pellets C. Pellets A had the highest bulk density (670 kg·m^{-3}), followed by pellets B with 630 kg·m^{-3} and pellets C with 610 kg·m^{-3}. The measured parameters of the pellets tested are shown in Table 2.

Table 2. Characteristics of the wood pellets tested.

Parameter	Unit	Pellets A	Pellets B	Pellets C	Testing Method
Net calorific value	MJ·kg^{-1}	17.23	17.21	17.53	PN-EN ISO 18125:2017-07
Moisture content	%	8.2	8.4	7.5	PN-EN ISO 18134-1:2015-11
Ash content	%	0.53	0.41	0.31	PN-EN ISO 18122:2016-01
Volatile matter	%	84.72	85.14	85.87	PN-EN ISO 18123:2016-01
Bulk density	kg·m^{-3}	670	630	610	PN-EN ISO 17828:2016-02

Before each test, the fuel feeding and airflow parameters were adjusted to achieve the set outputs independently for each burner and fuel. For both the boiler with the moving grate burner and the experimental burner, the combustion process parameters and settings were adjusted, including the fuel feeding time, fuel feeding break time, fan output and blower aperture width (see Table 3 for a summary of the parameters). These adjustments were made in order to achieve the set value of heating power:

- 16 kW (+/−10%) nominal heating capacity (100% output)—moving grate burner and experimental burner;
- 4.8 kW (+/−10%) minimum heating capacity (30% output)—experimental burner.

Table 3. Boiler settings during combustion; full and minimal load.

Type of Wood Pellet and Heating Capacity	Fuel Feeding Time [s]	Fuel Feeding Break Time [s]	Fan Output [%]	Blower Aperture Width [cm]
Type of pellet burner		Moving grate burner		
Pellets A 100%	8	6	40	full
Pellets B 100%	8	6	40	full
Pellets C 100%	8	6	40	full
Type of pellet burner		Experimental burner		
Pellets A 100%	8	8	22	full
Pellets A 30%	2	10	5	5
Pellets B 100%	8	6	34	3
Pellets B 30%	2	9	5	5
Pellets C 100%	8	6	34	3
Pellets C 30%	2	9	4	5

In the next step, the emissions of CO, NOx, dust and volatile organic compounds (VOCs) were measured during the combustion of pellets A, B and C in the boiler with the integrated reference burner and the experimental burner. Then, the statistical averages for the obtained emission measurement results were calculated. Further, each value of the abovementioned emissions was converted to a 10% concentration of oxygen in the flue gas. Emissions were compared at nominal heating capacity (100%) for the boiler with the reference burner (Uni-Max) and the experimental burner in the course of burning the three types of pellets. In the case of carbon monoxide emissions, higher pollution levels were recorded for the experimental burner for all the pellet types tested. The highest CO concentration of 201.2 mg·m^{-3} was measured for the experimental burner when burning pellets C. In contrast, the lowest CO level for the experimental burner was recorded at 78.5 mg·m^{-3} when pellets B were combusted. For the Uni-Max burner, the CO pollution level for pellet A was approximately 62 mg·m^{-3}, and for pellet B, approximately 55 mg·m^{-3}. The lowest CO value for this burner was 37 mg·m^{-3}—pellets B (Figure 7). All CO emissions measured for the pellets at full load were well below 500 mg·m^{-3}, which is the limit for class 5 boilers according to PN-EN 303-5:2012.

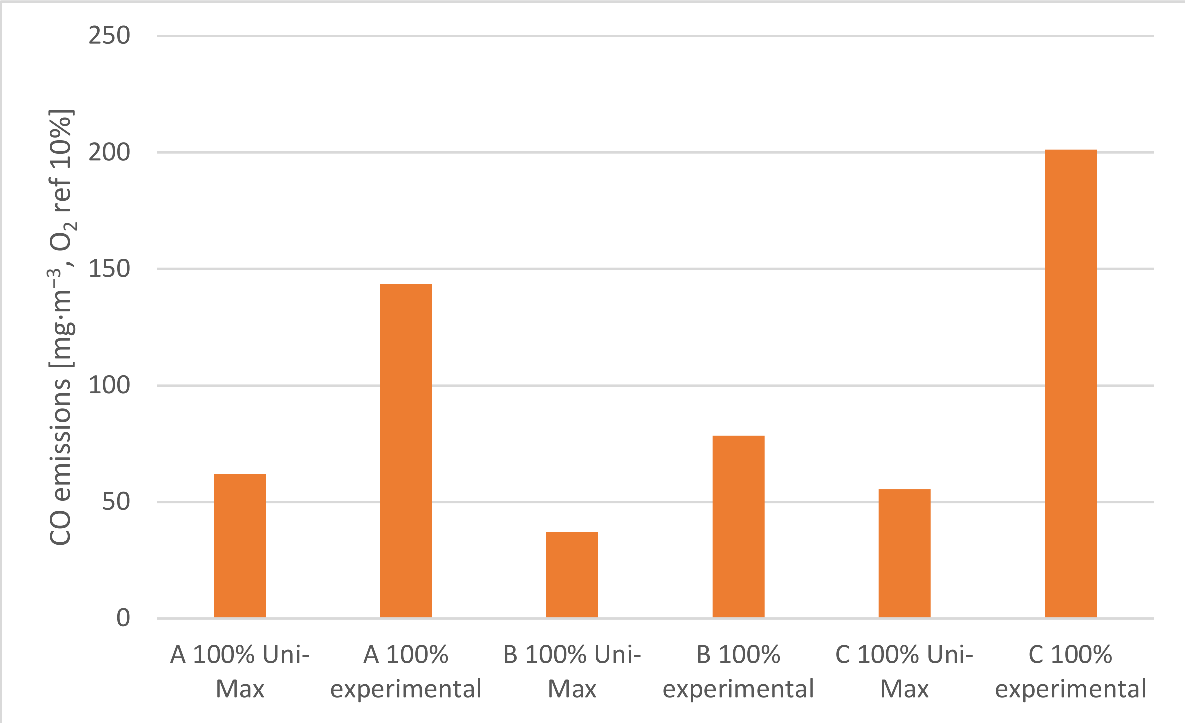


Figure 7. Comparison of average statistical CO emissions from the combustion of three types of wood pellets in two different burners at full load.

Higher NOx emission values were recorded in the course of comparing the combustion of type A, B and C pellets for the Uni-Max burner. The highest values were measured for pellets C (Uni-Max burner, approx. 204 mg·m^{-3}; the experimental burner, approximately 186 mg·m^{-3}). For pellets A and B, similar emission values were recorded, i.e., approximately 180 mg·m^{-3} in both cases for the Uni-Max burner and approximately 150 mg·m^{-3} for the experimental burner, see Figure 8. With regard to the particulate dust emissions for pellets A, lower emissions were found for the experimental burner (18.5 mg·m^{-3}) than for the Uni-Max burner (21.6 mg·m^{-3}). The opposite was true for pellets B and C, where lower dust emission values were measured for the Uni-Max burner (12.4 mg·m^{-3} with 13.6 mg·m^{-3}, respectively) than the experimental one (Figure 9). The highest volatile organic compound emissions were recorded when pellets C were combusted in the experimental burner (2.9 mg·m^{-3}). The VOCs emissions for pellets A and B combusted in the boiler with the experimental burner were at the same level, i.e., 2.5 mg·m^{-3}. For the boiler with the Uni-Max burner, the lowest VOCs emissions were recorded for pellets B (1.2 mg·m^{-3}), and the highest emissions were recorded for pellets A at 1.7 mg·m^{-3} (Figure 10).

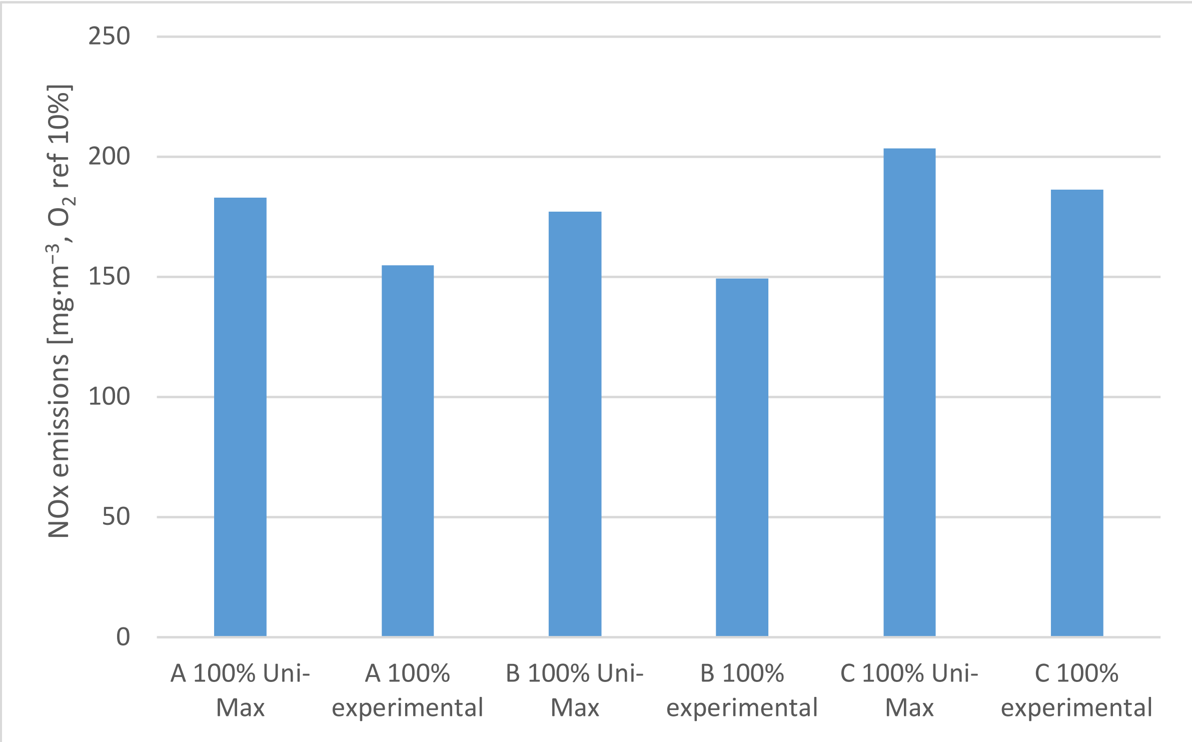


Figure 8. Comparison of average statistical NOx emissions from the combustion of three types of wood pellets in two different burners at full load.

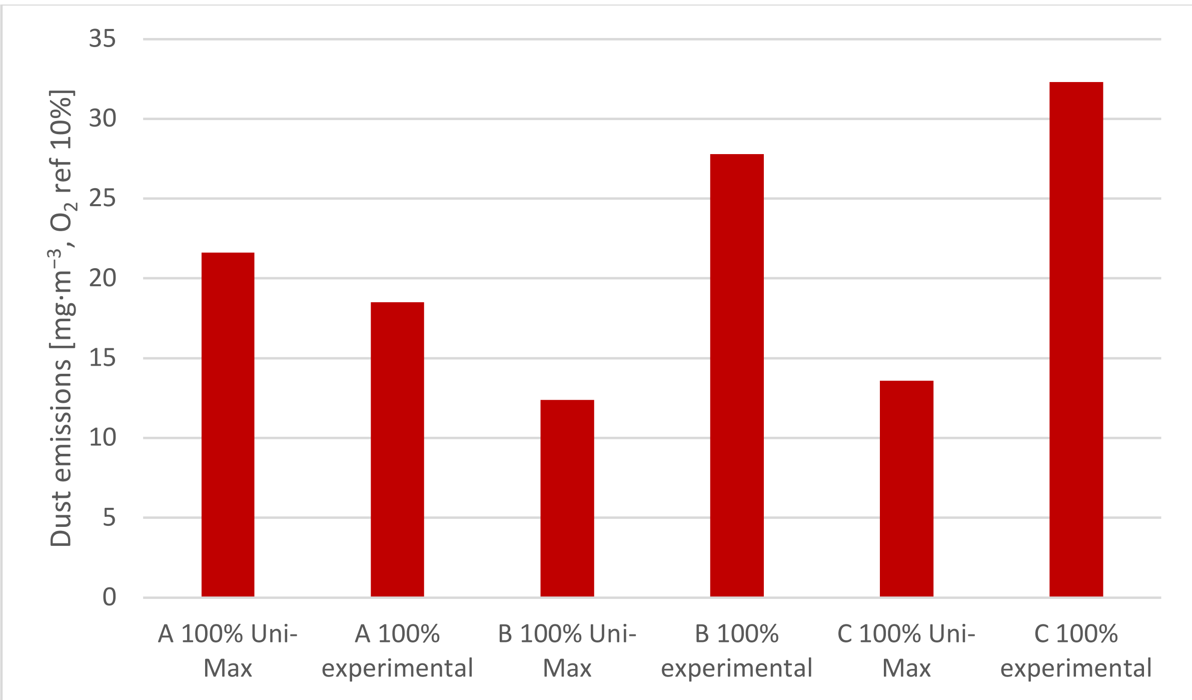


Figure 9. Comparison of average statistical dust emissions from the combustion of three types of wood pellets in two different burners at full load.

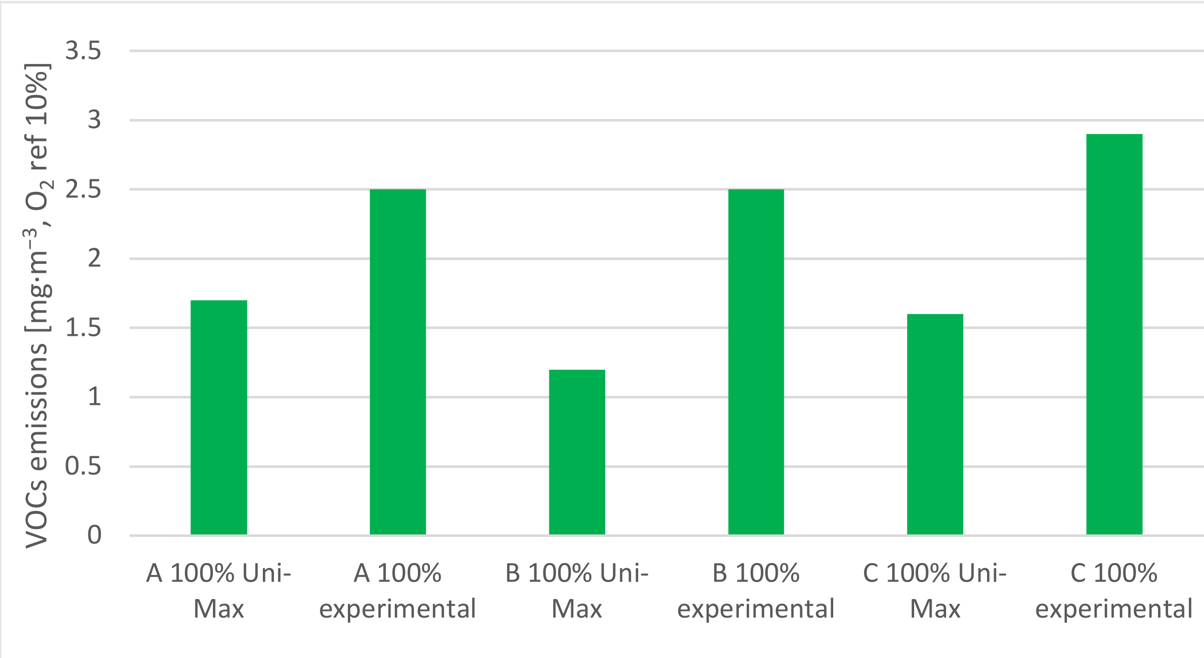


Figure 10. Comparison of average statistical VOCs emissions from the combustion of three types of wood pellets in two different burners at full load.

Emissions were also compared at the nominal (100%) and minimum (30%) heating capacity for the boiler with the experimental burner in the course of burning the three types of pellets. In the case of carbon monoxide emissions for the experimental burner, higher pollution levels were recorded during combustion at the minimum load than at full load for all three types of pellets. This is due to lower temperatures in the burner in the minimum load condition, which leads to incomplete combustion, leading to the production of CO [54]. For both the nominal and the minimum heating capacity mode, the emission of carbon monoxide when burning wood pellets A, B and C met the requirements of the PN-EN 303-5:2012 standard. It is worth noting that when combusted in the boiler with the experimental burner, CO emissions for all three pellet types were slightly higher at the minimum load compared with the nominal load. CO emissions were 1.2-times higher for pellets A, 2.3-times higher for pellets B and 1.3-times higher for pellets C.

When comparing the above results with the test results for the combustion of wood pellets in the boiler with a moving grate burner from Uni-Max, there is little difference between the CO emissions at minimum and nominal loads. In the testing carried out for wood pellets at the minimum load of the boiler (30%) with a moving grate burner (Uni-Max), CO emissions were 370 mg·m^{-3}. This was 4.1-times higher than at full boiler load (100%), where the emission was 90.5 mg·m^{-3} [51].

Considering NOx emissions for pellets A and B for both the full boiler load and minimum load, similar levels were measured at approximately 150 mg·m^{-3}. For pellets C, the emissions from combustion were lower at the minimum load (approximately 174 mg·m^{-3}) than for nominal combustion at approximately 186 mg·m^{-3}. Particulate dust emissions during operation at nominal boiler load were higher than at the minimum load. The highest emissions were measured when burning pellets B and C at full load (27.8 mg·m^{-3}—pellets B and 32.3 mg·m^{-3}—pellets C, respectively). In contrast, the lowest dust emissions were measured for pellets A at the minimum load (15.2 mg·m^{-3}). Regarding volatile organic compounds (VOCs), higher emission values were found for the boiler operating at the minimum load; the highest emission value for the boiler operating at the minimum load was measured when combusting pellets C (7.4 mg·m^{-3}). In contrast, very similar VOCs values of 2.5–2.9 mg·m^{-3} were recorded the boiler operating at the full load when burning all three pellet types (Figure 11).

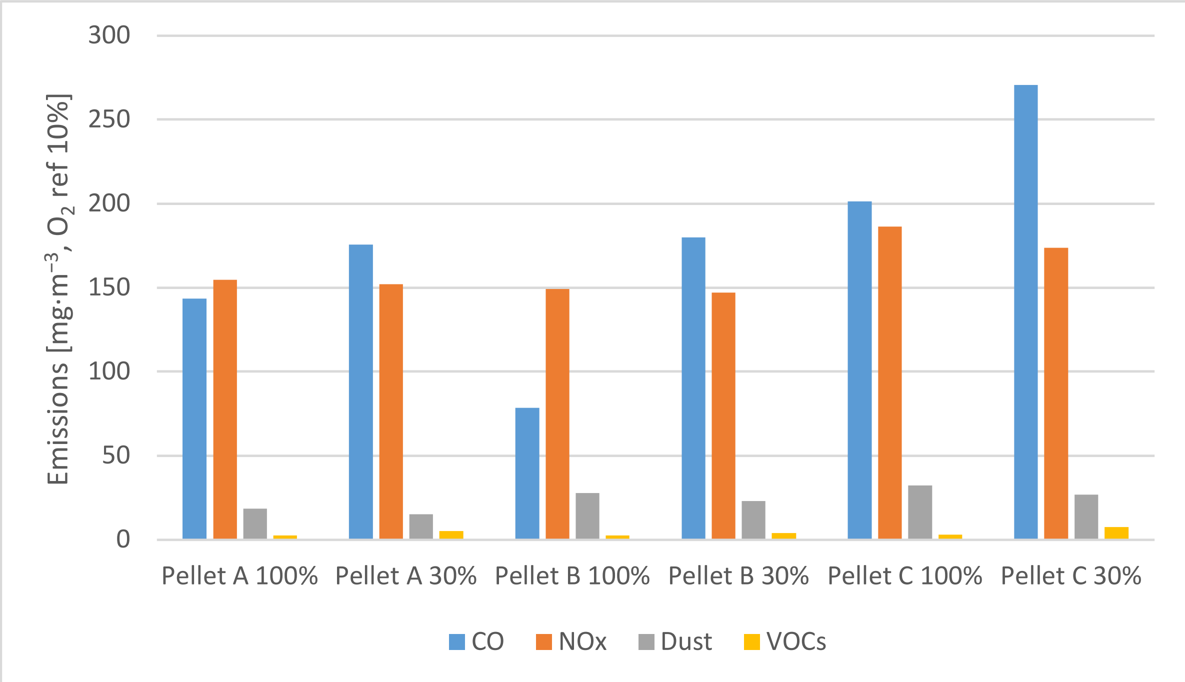


Figure 11. Comparison of average statistical emissions from the combustion of three types of wood pellets in experimental burners.

During the test combustion, the thermal efficiency of the η_{th} boiler was calculated according to Formula (1). The thermal efficiencies when burning pellets A, B and C, respectively, for the boiler with the experimental burner (72.9% for pellets A, 77.0% for pellets B and 74.0% for pellets C), were compared with the thermal efficiencies when the reference burner was fitted (73.5% for pellets A, 74.8% for pellets B and 76.7% for pellets C) (Figure 12). The efficiencies obtained for pellet combustion using two burners were not high because the boiler was not thermally insulated during the operation and had high heat losses to the laboratory room.

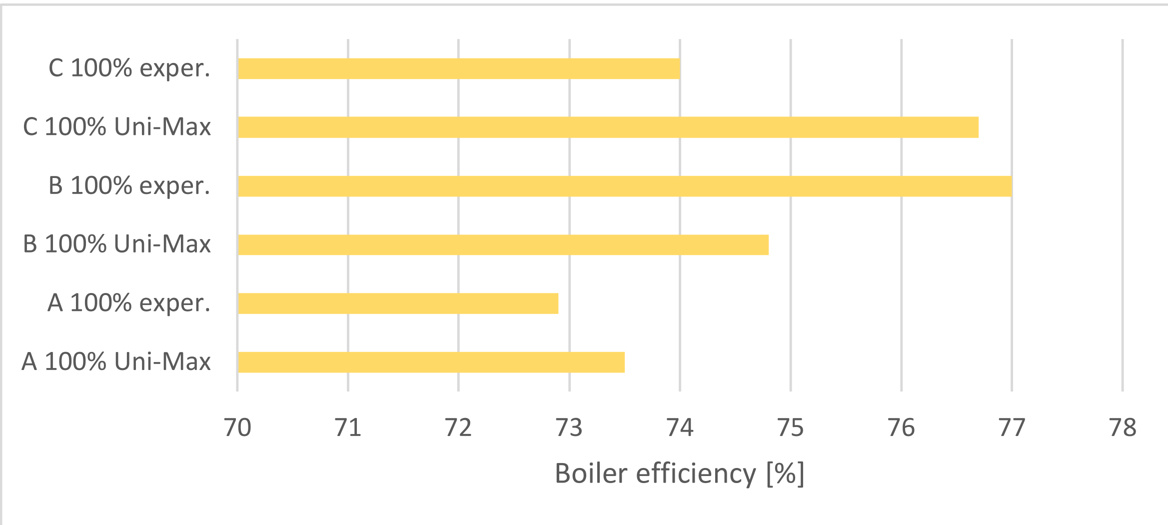


Figure 12. Thermal efficiency of the boiler for two burners when burning three types of commercial wood pellets at full load.

The combustion efficiencies η_c for the reference burner were as follows: 93.1% for pellets A, 93.7% for pellets B and 93.6% for pellets C. For the experimental burner, these efficiencies were 94.7% for pellets A, 93.6% for pellets B and 92.4% for pellets C) (Figure 13). The combustion efficiencies obtained for each of the burners and fuels were at a similar level, i.e., approximately 93.5%. For the experimental burner and pellets A, the efficiency was about 1% higher, and for pellets C, the efficiency was about 1% lower. The average boiler performance parameters for the two burners, as well as the emissions and efficiencies in connection with combustion of the three pellet types, are shown in Table 4.

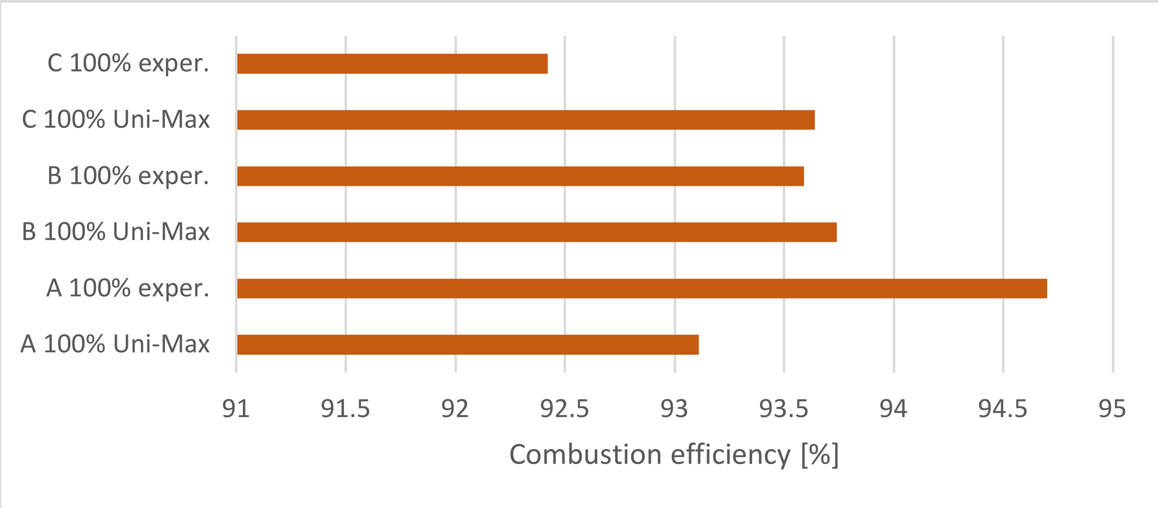


Figure 13. Combustion efficiency for two burners when burning three types of commercial wood pellets at full load.

Table 4. Average working parameters of the boiler for two burners and emissions from the combustion of three types of pellets.

	Pellets A 100% Uni-Max	Pellets A 100% Exper.	Pellets A 30% Exper.	Pellets B 100% Uni-Max	Pellets B 100% Exper.	Pellets B 30% Exper.	Pellets C 100% Uni-Max	Pellets C 100% Exper.	Pellets C 30% Exper.
Outlet temperature [°C]	72.0	70.5	71.1	71.8	71.4	70.2	71.4	70.1	70.8
Inlet temperature [°C]	64.0	62.7	68.7	64.1	63.2	67.8	63.9	61.9	68.5
Water flow rate [l·h^{-1}]	1800	1800	1800	1800	1800	1800	1800	1800	1800
Heating capacity [kW]	16.7	16.2	5.1	16.3	17.1	4.9	15.7	17.3	4.8
Fuel consumption [kg·h^{-1}]	4.75	4.65	1.45	4.55	4.63	1.30	4.20	4.8	1.5
Flue gas temperature [°C]	104.1	98.3	71.2	103.6	113.6	72.1	101.2	112.8	69.7
Outside temperature [°C]	27.8	28.0	25.1	19.9	23.4	24.9	20.4	22.4	21.4
O_2 [%]	9.5	9.6	15.2	9.2	8.8	15.0	9.8	10.6	15.6
CO_2 [%]	7.3	8.7	4.3	8.8	9.2	4.4	8.3	7.8	4.1
η_{th} [%]	73.5	72.9	68.5	74.8	77.0	78.0	76.7	74.0	66.0
η_c [%]	93.1	94.7	92.8	93.7	93.6	93.0	93.6	92.4	92.1
CO [mg·m^{-3}, 10% O_2]	62.1	143.5	175.7	37.0	78.5	180.1	55.4	201.2	270.6
NO_x [mg·/m^{-3}, 10% O_2]	182.9	154.7	152.1	177.1	149.2	147.0	203.4	186.2	173.8
Dust [mg·m^{-3}, 10% O_2]	21.6	18.5	15.2	12.4	27.8	23.0	13.6	32.3	26.9
VOCs [mg·m^{-3}, 10% O_2]	1.7	2.5	5.2	1.2	2.5	4.0	1.6	2.9	7.4

The test compared the studied pellet burners (moving grate and overfed experimental burner) to other pellet burners on the market, showing that the tested burners have emissions on a similar level. During the combustion of wood pellets, the underfed pellet boiler (with a heating capacity of 27 kW), described in [55], had 32 mg·m^{-3} CO emission, 260 mg·m^{-3} NOx emission and had a combustion efficiency of 93%. During the test, the moving grate burner boiler for the pellets (with a heating capacity of 51.5 kW) remitted 195 mg·m^{-3} CO and 243 mg·m^{-3} NOx with a combustion efficiency of 94% [55]. For the overfed state-of-the-art boiler with 15 kW heating capacity, the CO emission was really low at 5.5 mg·m^{-3}, with 0.55 mg·m^{-3} for VOC emission, 230 mg·m^{-3} for NOx emission and 33 mg·m^{-3} of dust emission [56]. That boiler had significantly lower CO emission comparing to the tested ones. For the 20 kW rotary furnace pellet boiler, for the nominal capacity, the CO emission was 695 mg·m^{-3} and NOx emission was 156 mg·m^{-3} [57]. The research described in [58] shows that emissions strictly depend on the burner and boiler specific construction. The description of two overfed boilers (15 and 20 kW heating capacities) showed significant differences in the measured emissions. For the 15 kW boiler with an overfed pellet furnace, the CO emission was 609 mg·m^{-3}, NOx emission was 36 mg·m^{-3} and dust emission was 5 mg·m^{-3}. For the 20 kW boiler with an overfed pellet furnace, the CO emission was 78 mg·m^{-3}, NOx emission was 88 mg·m^{-3} and dust emission was 3.6 mg·m^{-3}. The above results have been converted to the 10% O_2 reference.

The results obtained during testing of moving grate and experimental overfed pellet burner may be an introduction to work on improving the quality of combustion and thus reducing pollutants.

4. Conclusions and Remarks

As part of the testing, the statistical averages of emissions were compared when burning at full power for a reference burner and a test burner. Three brands of commercial wood pellets commonly found in Poland were used as fuel. The obtained results led to the following conclusions:

- The levels of CO, NOx, dust and VOCs were similar for combustion at full power using the burners tested;
- Taking into account the pollution levels at combustion, it can be said that the difference in CO emissions at full and minimum combustion was lower for the experimental burner compared with the moving grate burner (reference burner);
- It is worth noting that the requirements of EN 303-5:2012 were met by all the samples and configurations tested (pellets A, B and C experimental burner and Uni-Max, and 100% and 30% boiler loading). The combustion efficiencies η_c obtained of pellets A, B and C for each of the burners were at a similar level, i.e., approximately 93.5%;
- For the experimental burner and pellets A, the efficiency was 1% about higher, and for the experimental burner and pellets C, the efficiency was about 1% lower.

In summary, it can be concluded that the experimental overfed burner under consideration can be successfully used as a solid fuel boiler to burn wood pellets. The results were particularly advantageous with regard to emissions from burning a minimum load (30%) of wood pellets with the experimental burner as compared with the Uni-Max burner. Appropriate management of the selection and purchase process of the heat source (boiler and burner) and the choice of fuel purchased and used (type, from a specific manufacturer) can significantly influence the effectiveness (efficiency) of the combustion process, the costs incurred by users and the amount of pollutants emitted during the combustion process.

In addition, the carried out experimental tests and measures allow us to look at positive expectation on the decarbonisation and the goal of achieving climate neutrality by 2050. Furthermore, new rationale has emerged in EU countries implying even greater use of alternative energy sources. One of the reasons is the low supply of fossil fuels (hydrocarbons) due to the difficult and complex political and economic situation. Another reason is the high uncertainty about the future supply of hydrocarbons associated, inter alia, with the war in Ukraine. In Poland, the use of modern and ecological boilers adapted to burning wood pellets is becoming an increasingly interesting alternative in the context of the problem of air pollution caused mainly by the household and municipal sector, which uses outdated designs of coal-fired boilers, as well as using low-quality coal and the large increase in the price of this fuel.

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