

Article

Low Emissions Resulting from Combustion of Forest Biomass in a Small Scale Heating Device

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Received: 5 September 2020; Accepted: 19 October 2020; Published: 20 October 2020



Abstract: The paper concerns the analysis of harmful emissions during the combustion process in households. The subject of the analysis is a low emission heating device with an output of 50 kW for burning biomass of forest origin (low-quality hardwoods or softwoods). The proposed boiler is automatically fed from the connected container by means of a screw conveyor. In this way, the optimum amount of fuel is supplied for maximum heat output (adjustment of the ratio of primary air to fuel). The proposed biomass heating system is equipped with a primary and secondary air supply system and exhaust gas sensors. This ensures optimal regulation of the air mixture and efficient and clean combustion. Proper control of the combustion process, control of the air supply by means of a lambda sensor and power control of the system ensure a low-emission combustion process. The system precisely adjusts to the heat demand. This results in highly efficient heating technology with low operating costs. In the presented work, the emission of exhaust gases from the proposed heating device during the combustion of woodchips and beech–oak pellets were measured. It is demonstrated that the proposed design of the boiler equipped with intelligent control significantly reduces emissions when the biomass solid fuels are used, e.g., CO emissions from beech and oak chips and pellets in the low-emission boiler—18 extract pipes shows the value <100 ppm, which is even lower than when gas is burned in the other boilers; on the other hand, the pine chips show even higher emission when burned in the low-emission burner. Consequently, the choice of biomass source and form of the fuel play some role in the emissions observed.

Keywords: heating device; construction; low emissions; woodchips; pellets; biomass

1. Introduction

The level of public awareness of ecology, environmental cleanliness and the emission of harmful pollutants into the atmosphere is regularly increasing. The long-term process of economic change shows that over time the importance of sustainable development principles and the consequences of high greenhouse gas emissions are increasingly important.

According to the Global Carbon Project (GCP), 36.81 billion tonnes of CO₂ (GtCO₂) were emitted into the atmosphere in 2019. This means an increase of only 0.24 GtCO₂ (0.6%) compared to 2018. The increase in global emissions in 2019 was almost entirely caused by China. This country has

increased its CO₂ production by 0.26 GtCO₂. The rest of the world has reduced its emissions by −0.02 GtCO₂. This was due to a reduction in coal consumption in the US and Europe, as well as a slowdown in the Indian economy compared to previous years [1].

Increasingly restrictive regulations and global environmental organisations regularly seek to improve the environment. A key issue that could not be resolved at COP24 in 2018 and at COP25 in Madrid was Article 6 of the Paris Agreement, which provides for the introduction of market mechanisms as an instrument to combat climate change.

Scientific and technological progress in the field of robotization, mechanization, automation, energy and artificial intelligence is changing the world economy [2–4]. The priority is to develop new industries based on technologies capable of creating breakthrough products [5–7]. The development of scientific and technical thought has led to the development of high-tech industries in many countries, primarily those highly developed economically [8,9]. The strategy of innovation and economic efficiency is crucial [10,11].

As populations grow, energy consumptions and gas emissions into the atmosphere increase [12–14]. The largest emitters of atmospheric pollutants are residential buildings and road transport [15,16]. Individually heated residential buildings are the main source of low emissions, i.e., harmful emissions of gases and dust at low altitude [17–19]. When speaking of low altitude, it is understood that emitters, such as chimneys and other emission sources, are located at a height of not more than 40 m (usually up to 10 m) [20,21]. The causes of low emissions related to private buildings include: Heating houses with poor quality fuel, burning waste, lack of standards for fuels used in households, the use of outdated boilers and combustion technologies inadequate for insulation of buildings [22–24]. A common feature of low emission sources is the possibility of a strong impact on air quality in the immediate vicinity of the emission place [25,26]. Despite relatively low loads of pollutants released into the air, these sources can cause high local concentrations of substances in the air due to the low altitude of the emission point [27–29]. It has to be pointed out that widely distributed local emission points are also contributing to the troposphere greenhouse gases concentration causing, as is widely discussed, the effect of global warming; see [30] or [31].

One of the factors affecting the generation of low emissions is the use of outdated combustion installations [32,33]. Devices used in single-family housing are usually of low thermal efficiency, which often does not exceed 50% on an annual average [34,35]. Moreover, installations of this type do not have an adequate secondary air supply system, which would operate in a controlled manner and would therefore be highly efficient [36,37]. The above factors contribute to high emission of pollutants to the environment, which is a threat to the users and their immediate surroundings [38,39]. In Poland, over 50% of energy in the municipal and housing sectors is obtained from coal, then from natural gas, liquid fuels and renewable energy sources (solar collectors, photovoltaic panels) [40–46]. The use of low-quality fuel and inappropriate selection of combustion method have a large impact on the discussed problem of low emissions [47,48]. For this reason, the quality of the supplied fuel is of great importance, as it contributes to the achievement of certain energy and emission parameters of the boilers, set out by the relevant standards (e.g., PN-EN 303-5: 2012) [49,50]. Considering the effect of low emissions, they need to be counteracted and appropriate methods and techniques should be applied to reduce them, as the European Union does through appropriate legislation [51–54]. It is reported that 70% of single-family houses use hard coal for heating [55].

On the other hand, according to data from electricity producers, the share of coal in electricity production in 2019 was 73.6%, while the share of natural gas was around 5% and renewable sources provided just over 14% [56].

The design of a heating system should be determined by a number of factors, e.g., fuel characteristics, heat output of the device and heat demand [57–60]. The device should be as much as possible maintenance free; therefore, an automated system of fuel supply to the combustion chamber should be used, and the control system should ensure adequate heat transfer as well as provide the right amount of air for optimal combustion [61–64].

When compared to the combustion of liquid or gaseous fuels, the combustion of solids involves not only significantly higher expenses in terms of transport and storage of fuels, but also the design of the furnace. The geometry of the combustion chamber and the regulation of the combustion process require much more attention [65–67]. When burning biomass, a much larger combustion chamber is required, which should also be divided into different zones (degassing and burnout zones) with different air supply (primary and secondary air) and should generally not be cooled [68–70].

The energetic use of biomass is a complex process that can only be optimally exploited with appropriate measurement, control and regulation technology [71,72]. Continuous measurement of the relevant emissions (CO and NO_x) and feedback from the control system optimize the system's emission behaviour [73,74]. In addition, a documentation of measured values can help to determine the cause of a malfunction. Biomass-based heating systems are usually equipped with properly programmed logic controllers or microcontroller systems [75,76]. In addition, various sensors and actuating devices that are installed at the process level and that provide or process the signals are part of the basic instrumentation equipment and control technology. The most important control tasks for a biomass boiler include adjusting the boiler output to the power demand (power control between 30 and 100% of the nominal heat output) and optimization of combustion by adjusting the combustion air to the current air demand (combustion control with the lambda probe and exhaust gas recirculation) [77–80]. Another important task of measurement and control technology is the device monitoring. In the event of major accidents, the system must be automatically shut down or at least parts of the system must be taken out of service [81,82].

The excess air ratio (λ) defines the ratio of the mass of air in which the fuel is burned to the amount of air required to burn the fuel completely (stoichiometric mixture). The ideal mixture—stoichiometric—is one in which for every 1 kg of burnt fuel there is 14.7 kg of air (then $\lambda = 1$). Combustion at $\lambda = 1$ is called stoichiometric mixture combustion ($\lambda > 1$ lean mixture combustion, $\lambda < 1$ rich mixture combustion) [83,84]. The stoichiometric (theoretical) amount of air can be calculated from the analysis of chemical reaction equations occurring during combustion of a specific fuel. In order to achieve complete combustion, it is usually necessary to supply more air than is apparent from the stoichiometric equations. This is particularly true for solid fuels (e.g., coal dust). If gaseous or well vaporised liquid fuels are burned, the amount of air required to achieve complete combustion is not much greater than for stoichiometric [85].

In practice, to obtain a stoichiometric mixture, values of λ in the range -0.97 – 1.03 are adopted. In order to optimally record and control varying output parameters, combustion conditions and fuel quality changes at different humidity levels and to keep emissions to a minimum, a sensor is required that will send the relevant values to the combustion control system. For this purpose, a heated zirconium dioxide probe (insensitive to dust) is often used, which detects the O₂ content in the exhaust gas and generates a proportional electric output signal [86,87].

The furnace temperature controller determines the relationship between the oxygen-rich primary air and the low-oxygen cooled exhaust gas [88–91]. However, if the exhaust gas recirculation is not sufficient to limit the temperature in the combustion chamber, cooling with secondary air is also applied (override control). By returning the exhaust gas from the heat exchanger to the combustion zone, the proportion of oxygen is reduced but on the other hand the combustion temperature drops. The combustion temperature depends, among other things, on the calorific value of the fuel. The fuel and air for combustion together form a combustible mixture with a characteristic heat emission value. If the exhaust gas is added to the fuel-oxidation mixture, the heat emitted by the whole mixture and thus the achievable combustion temperature will be reduced. This recirculation is used to avoid thermal overload of the fireclay surface, to reduce slag formation in the combustion chamber and to regulate oxygen. The exhaust gas recirculation system is used for fuels with high calorific value, low ash melting point and high nitrogen content in the fuel [92–95].

2. Tests and Measurements of Examples of the Devices Used

The research described in [93] was the reference point for the proposed new concept of a heating device. The research object described in the literature was a gas burner regulated in the power range of 12 to 25 kW, widely used in households. A special flame plate is used in the burner, which supplies half of the combustion air flowing through the holes, and directs the rest under the plate block. The device is equipped with a blower and insulated exhaust gas recirculation.

Research tests were carried out in the power range of 13 kW to 18 kW with a variable amount of air and variable exhaust gas circulation. The exhaust emission and the degree of oxidation were tested at the same air ratio. The issue of emissions at lower power (i.e., 13 kW) was tested with three air proportions ($\lambda = \{1.1; 1.2; 1.3\}$) and different values of the exhaust gas recirculation rate R . The R parameter is defined as the ratio of recirculation and the exhaust mass flow rates produced. The energy balance of the test object was established for one air ratio λ and R . In the case of setting the power to 18 kW, the tests were carried out at $R = 2$ and $\lambda = 1.1$.

The main aim of the study described in the literature was to investigate the effect of the exhaust gas extraction system on the combustion characteristics in a low-power pellet boiler. In this context, two different designs of pellet boilers were designed, manufactured and tested. Both research structures had a two-stage exhaust gas extraction system, while the first one had a smaller number of exhaust gas extraction pipes. Boiler 1 had six exhaust gas exhaust pipes; boiler 2 had 11 pipes.

The effect of various gas flows through the boilers on the flame temperature, exhaust gas temperature, thermal efficiency and exhaust gas emissions of O_2 , CO , CO_2 and NO_x was investigated and the results were compared with one another. The experiment was carried out using pellets made of beech and pine timber. The results showed that adding pipes to the first boiler in the exhaust gas extraction system lowered the average exhaust gas temperature from 87.6 °C to 76.9 °C.

The efficiency of boiler 2 reached a value of 92.3% and was almost 1.3% higher than that of boiler 1. It was observed that the addition of exhaust pipes to the first boiler draught did not significantly affect NO_x emissions, which amounted to about 45–47 ppm.

The purpose of this manuscript is to investigate emissions during combustion of pine chips (*Pinus sylvestris*) and beech and oak pellets in the designed heating device (low-emission heating device for residential buildings). The results of the analysis were compared with those available in the literature. The comparison was made between devices powered by biofuels with similar parameters, e.g., moisture content, bulk density. Additionally, the manuscript analyses exhaust emissions in the context of lignite.

The analysed design solution is protected by patent application no. P.432065, owned by the co-authors of the manuscript.

3. Materials and Methods

Materials

The subject of the research was a 50 kW boiler fired with forest biomass, in particular woodchips, to economically heat households with different needs.

The proposed heating system for biomass of forest origin, in particular for wood chips, consists of: Fuel storage room with a mixing shovel, fuel transport system—screw conveyor, stove, boiler, control system, exhaust gas discharge system—18 exhaust pipes, ash extractor. The main dimensions of the boiler are presented in Table 1.

Both the boiler and the burner are made of heat-resistant sheet metal (boiler construction: 16Mo3 steel; heat-resistant steel H20N12S2; boiler steel P265GH; external jacket covering the thermal insulation—aluzinc steel). By using a fuel storage, the fuel is not exposed to external factors, which would deteriorate its quality, and the transport system ensures maintenance-free operation of the device.

Table 1. Main dimensions of the boiler.

Parameter	Dimension (mm)
Boiler height	2350
Cleaning hatch height	160
Height to cleaning hatch	2110
Combustion chamber height	1310
Dimensions of exhaust pipes	$\text{Ø}82 \times 6.3 \times 820$
Combustion chamber wall thickness	8
Ash extract	$\text{Ø}101$
Boiler width	662
Width of exhaust pipes spacing	446

The diagram of the burner used in the heating system is shown in Figure 1, while the diagram of a forest biomass-based boiler, along with the measuring points, is shown further in the manuscript.

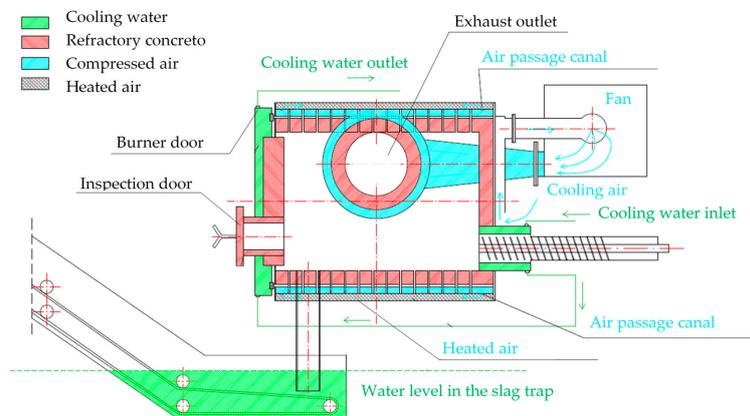
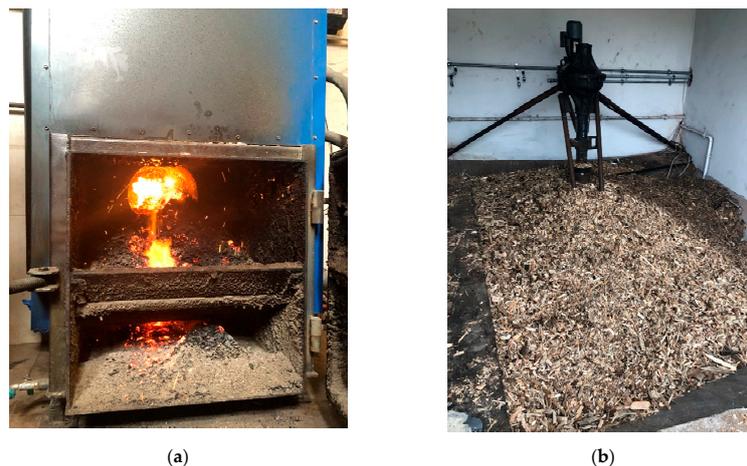
**Figure 1.** Burner used in the heating system.

Figure 2a shows the combustion chamber of the analyzed 50 kW boiler, and Figure 2b shows the fuel storage equipped with a mixer, and filled with pine chips.

**Figure 2.** Low-emission heating devices: (a) Combustion chamber; (b) fuel storage with a mixer.

The boiler is automatically fed from a connected storage via a screw conveyor. In this way, the optimal amount of fuel is always supplied to achieve maximum thermal efficiency. The biomass-based heating system is equipped with a primary and secondary air supply system and exhaust gas sensors. This ensures optimal regulation of the air mixture as well as efficient and clean combustion. The system precisely adjusts itself to the actual heat demand.

To determine the actual emission during the combustion, the Ecom EN2 (Ecom GmbH, Iserlohn, Germany) exhaust gas analyzer was used (Figure 3) with a measuring range of 0–4000 ppm and accuracy up to 1 ppm.



Figure 3. Exhaust gas analyzer with a measuring probe.

Basing on the data obtained from the producers of the fuels, the elemental composition of pine chips, beech and oak pellets was taken into account in computations of the emission of exhaust gases and greenhouse gases. Under operating conditions, users of boilers (e.g., biofuel fuelled) are capable of measuring the moisture content, calorific value and calorific value of the fuel. On the other hand, they are not able to measure (determine) the elementary composition of biomass because laboratory measurements are needed for this purpose.

The following list contains a collection of the most important quantities used in calculations, together with appropriate symbols and units (Table 2).

Table 2. Symbols and units used in calculations [96–100].

Parameter	Description	Unit
m	share of the element in the fuel	$\left[\frac{\text{kg component}}{\text{kg fuel}} \right]$
N	atomic mass of element	$\left[\frac{\text{kg component}}{\text{kmol component}} \right]$
M_{O_2}	molecular mass of oxygen	$[u]$
$n_{\text{O}_2\text{-min}}$	minimum oxygen demand (molar)	$\left[\frac{\text{kmol O}_2}{\text{kg fuel}} \right]$
λ	excess air for solid fuels	$[-]$
$n_{\text{p min}}$	minimum air demand	$\left[\frac{\text{kmol air}}{\text{kg fuel}} \right]$
n'_{H}	molar fraction of hydrogen in the fuel	$\left[\frac{\text{kmol H}}{\text{kg fuel}} \right]$
χ_{air}	molar degree of air humidity	$\left[\frac{\text{kmol H}_2\text{O}}{\text{kg dry air}} \right]$
$n'_{\text{H}_2\text{O}}$	molar fraction of water vapor in the fuel	$\left[\frac{\text{kmol H}_2\text{O}}{\text{kg fuel}} \right]$
n'_{p}	actual air demand	$\left[\frac{\text{kmol air}}{\text{kg fuel}} \right]$
n''_{x}	molar fraction of the exhaust gas component	$\left[\frac{\text{kmol x}}{\text{kg fuel}} \right]$
M	molecular weight	$[u]$
m_{x}	mass fraction of compound x in the exhaust gas	$\left[\frac{\text{kmol}}{\text{kg fuel}} \right]$
m_{sw}	relative amount of wet exhaust	$\left[\frac{\text{kg wet exhaust}}{\text{kg fuel (no balast)}} \right]$
m_{ash}	mass fraction of ash in the fuel	$\left[\frac{\text{kg ash}}{\text{kg fuel}} \right]$
m_{fuel}	fuel stream	$\left[\frac{\text{kg}}{\text{s}} \right]$
m_{spw}	exhaust mass flow	$\left[\frac{\text{kg}}{\text{s}} \right]$
$[x]$	share of compound x in exhaust gas composition	$\left[\frac{\text{kg x}}{\text{kg wet exhaust}} \right]$
w	dust lift indicator	$\left[\frac{\text{g}}{\text{Mg}} \right]$
η	dust extraction efficiency	$[\%]$
K	flammable content in dust	$[\%]$
C	mass fraction of carbon in the fuel	$\left[\frac{\text{kg}}{\text{kg fuel}} \right]$
H	mass fraction of hydrogen in the fuel	$\left[\frac{\text{kg}}{\text{kg fuel}} \right]$
S	mass fraction of sulfur in the fuel	$\left[\frac{\text{kg}}{\text{kg fuel}} \right]$
O	mass fraction of oxygen in the fuel	$\left[\frac{\text{kg}}{\text{kg fuel}} \right]$

The formulas used for the calculations are listed below [96–100].

Molar proportions of fuel components:

$$n'_x = \frac{m}{N} \left[\frac{\text{kmol } x}{\text{kg fuel}} \right] \quad (1)$$

Minimum oxygen demand (by weight):

$$m_{\text{O}_2\text{min}} = \frac{8}{3}C + 8H + S - O \left[\frac{\text{kgO}_2}{\text{kg fuel}} \right] \quad (2)$$

Minimum oxygen demand (by weight):

$$n_{\text{O}_2\text{min}} = \frac{m_{\text{O}_2\text{min}}}{M_{\text{O}_2}} \left[\frac{\text{kmol O}_2}{\text{kg fuel}} \right] \quad (3)$$

Minimum air demand:

$$n_{\text{p min}} = \frac{n_{\text{O}_2\text{min}}}{\text{share of oxygen in the air}} \left[\frac{\text{kmol air}}{\text{kg fuel}} \right] \quad (4)$$

Actual air demand:

$$n'_p = \lambda \cdot n_{\text{p min}} \left[\frac{\text{kmol air}}{\text{kg fuel}} \right] \quad (5)$$

Molar fraction of oxygen in the exhaust gas:

$$n''_{\text{O}_2} = 0,21(\lambda - 1) \cdot n_{\text{p min}} \left[\frac{\text{kmolO}_2}{\text{kg fuel}} \right] \quad (6)$$

Molar fraction of water vapor in the exhaust gas:

$$n''_{\text{H}_2\text{O}} = n'_H + X_{\text{pow}} \cdot n'_p + n'_{\text{H}_2\text{O}} \left[\frac{\text{kmolH}_2\text{O}}{\text{kg fuel}} \right] \quad (7)$$

Mass fraction of compound x in the exhaust gas:

$$m_x = n''_x \cdot M \left[\frac{\text{kg } x}{\text{kg fuel}} \right] \quad (8)$$

Share of compound x in the composition of wet exhaust gases:

$$[x] = \frac{m_x}{m_{\text{sw}}} \left[\frac{\text{kg } x}{\text{kg wet exhaust}} \right] \quad (9)$$

Part fuel stream (no ash):

$$m_p = (1 - m_{\text{ash}}) \cdot m_{\text{fuel}} \left[\frac{\text{kg}}{\text{s}} \right] \quad (10)$$

Exhaust mass flow:

$$m_{\text{spw}} = m_{\text{fuel}} \cdot m_{\text{sw}} \left[\frac{\text{kg}}{\text{h}} \right] \quad (11)$$

Compound x emissions in the exhaust:

$$m_{\text{ex}} = m_{\text{spw}} \cdot [x] \left[\frac{\text{kg}}{\text{h}} \right] \quad (12)$$

Dust content in the exhaust gas:

$$E_{\text{ash}} = m_{\text{fuel}} \cdot w \cdot \frac{100 - \eta}{100 - K} \left[\frac{\text{kg}}{\text{h}} \right] \quad (13)$$

4. Results and Discussion

Exhaust gas measurements were carried out on a 50 kW boiler while burning pine chips, oak–beech chips and beech and oak pellets (each fuel was burned separately). The measuring point is shown in Figure 4 as a red circle.

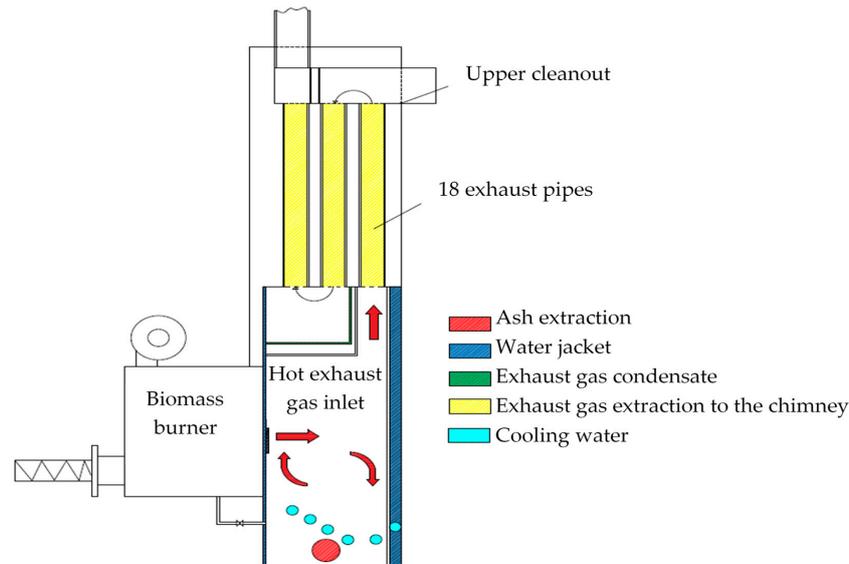


Figure 4. Analyzer burner measurements.

4.1. Burning the Wood-Derived Fuels

The physicochemical properties of all studied fuels (i.e., pine chips, oak–beech chips and beech–oak pellets) are presented in Table 3, while the results of measurements obtained from the exhaust gas analyzer are presented in Table 4.

Table 3. Physicochemical parameters of the fuels investigated [101–104].

Parameter	Pine Chips	Oak–Beech Chips	Beech–Oak Pellets
Transient moisture ¹	27%	24%	3.23%
Analytical moisture ²	9.11%	6.78%	2.80%
Ash	0.85%	0.70%	0.24%
Volatile matter	82.87%	84.77%	
Fixed carbon	7.17%	7.75%	
Sulphur	0.33%	0.29%	0.01%
Carbon	32.31%	31.60%	50.86%
Hydrogen	5.10%	7.70%	6.36%
Nitrogen	0.13%	0.18%	39.53%
Chlorine	<0.1%	<0.1%	0.2%
Oxygen	45%	45%	
Ash softening temperature	1200 °C	1200 °C	
Calorific value	10 MJ/kg	16 MJ/kg	
Lower calorific value in relation to the weight	3.7 kWh/kg	5.92 kWh/kg	
Lower calorific value in relation to the volume	750 kWh/m ³	1200 kWh/m ³	

¹ The term transient moisture refers to that part of the moisture that is weakly bound to the material and undergoes changes with the changes in the humidity of the surrounding air, while analytical moisture is determined in conditions assuring that the obtained value corresponds to the hygroscopic humidity. ² The sum of the components (analytical moisture, ash, volatile matter and fixed carbon) gives a value of 100%.

Table 4. Measurement results of the exhaust gas analyzer during combustion of pine woodchips of the fuels investigated.

Exhaust Component	Pine Woodchips	Oak–Beech Chips	Beech and Oak Pellets	Unit
O ₂ ¹	7.4	17.8	9.5	%
CO	255	97.33	83	ppm
NO	244	96.20	290	ppm
NO _x	256	104	304	ppm
CO ₂ ¹	13.1	5.0	4.3	%
η ²	92.1	96.5	97.7	%
Losses	7.9	5.04	5.1	%
λ	1.54	1.60	1.83	
Exhaust gas temperature	152	133.1	133.4	

¹ % for O₂ and CO₂ is the concentration by volume; ² η boiler thermal efficiency.

Transient moisture is the part of the water contained in solid fuel that is maintained on the surface of the grain. This moisture appears during transport or storage usually during rainfall and disappears e.g., when storing the material in a dry environment. It is determined by drying the damp fuel in the air usually at ambient temperature until it reaches equilibrium with ambient air humidity. The analytical moisture—contained in the analytical sample of the fuel used for analysis.

4.2. Calculation of Exhaust Gas Characteristics

Emission calculations were made for pine chips and beech and oak pellets are given in Table 5. The analytical composition of the all fuels investigated was shown in Table 4.

Table 5. Summary of calculation results for the characteristic values of exhaust gases.

Parameter	Pine Chips	Beech and Oak Pellet	Unit
Minimum oxygen demand for combustion by mass	0.743	1.46	$\frac{\text{kg O}_2}{\text{kg fuel}}$
Minimum oxygen demand for combustion (molar)	0.00232	0.0457	$\frac{\text{kmol O}_2}{\text{kg fuel}}$
Minimum air demand for combustion	0.111	0.217	$\frac{\text{kg air}}{\text{kg fuel}}$
Actual air demand for combustion	0.177	0.348	$\frac{\text{kg air}}{\text{kg fuel}}$
Total wet exhaust quantity	4.318	8.212	$\frac{\text{kg wet exhaust}}{\text{kg fuel (no balast)}}$
Stream of the fuel part without ash—ballast	2.97	2.98	$\frac{\text{kg}}{\text{h}}$
Wet exhaust gas mass flow	12.852	24.56	$\frac{\text{kg}}{\text{h}}$
CO ₂ emission	2.995	5.57	$\frac{\text{kg}}{\text{h}}$
SO ₂ emission	0.0197	0.0006	$\frac{\text{kg}}{\text{h}}$
N ₂ emission	7.313	14.39	$\frac{\text{kg}}{\text{h}}$
O ₂ emission	0.134	2.613	$\frac{\text{kg}}{\text{h}}$
H ₂ O emission	2.39	1.98	$\frac{\text{kg}}{\text{h}}$
Dust emission	0.000191	0.000054	$\frac{\text{kg}}{\text{h}}$

4.3. Summary of the Characteristics of a Low-Emission Heating Device

The proposed device is characterized by a low level of emissions into the atmosphere. Table 6 presents the results of the flue gas analysis performed along with the analysis of the flue gas of the gas burner and pellet boilers. The gas burner is characterized by the highest efficiency and the lowest flue gas temperature. The lowest emission of carbon monoxide and carbon dioxide was recorded during the combustion of beech and oak pellets. In the case of nitrogen oxide emission measurements, the lowest value was obtained in the beech–pine pellet boiler (11 exhaust pipes).

Table 6. Comparison of the exhaust gas analysis results from the test object with the literature data.

Quantity	Low-Emission Boiler—18 Extract Pipes	Low-Emission Boiler—18 Extract Pipes	Low-Emission Boiler—18 Extract Pipes	Gas Burner	Boiler—6 Extract Pipes	Boiler—11 Extract Pipes	Unit
Type of fuel	Pine chips	Oak-beech chips	Beech and oak pellets	Gas	Beech and pine pellets	Beech and pine pellets	
O ₂	7.4	17.8	9.5	5	13.6	13.4	%
CO	255	97.33	83	148	160	375	ppm
NO	244	96.20	290	22	-	-	ppm
NO _x	256	104	304	-	50	48	ppm
CO ₂	13.1	5	4.3	9	7.3	7.4	%
η	92.1	96.5	97.7	99.3	91.5	92.2	%
Loses	7.9	5.04	5.1	-	-	-	%
λ	1.54	1.60	1.83	1.3	-	-	-
Exhaust gas temperature	152	133.1	133.4	55.1	87.6	76.9	°C

The thermodynamic efficiency of the proposed technical solution (equipped with an exhaust system—18 exhaust pipes) exceeds 92%. According to the information resulting from the review of the technical solutions available on the market, the proposed design solution exceeds or at least equals the solutions available on the market [105,106]. The cost of purchasing the proposed construction solution is twice as low as competitive market solutions [107].

On the basis of the physicochemical parameters of pine chips and beech and oak pellets, calculations were made of exhaust emissions during combustion. The results were compared with the emission of lignite combustion (Table 7).

Table 7. Calculated emission of exhaust gases during the combustion of pine chips and beech and oak pellets in comparison with brown coal.

Exhaust Component	Emission—Pine Chips	Emission—Beech and Oak Pellets	Emission—Lignite	Unit
CO ₂	2.995	5.57	103.63	$\frac{\text{kg}}{\text{h}}$
SO ₂	0.0197	0.0006	1.62	$\frac{\text{kg}}{\text{h}}$
N ₂	7.313	14.39	447.7	$\frac{\text{kg}}{\text{h}}$
O ₂	0.134	2.613	50.93	$\frac{\text{kg}}{\text{h}}$
H ₂ O	2.39	1.98	44.13	$\frac{\text{kg}}{\text{h}}$
Dust	0.000191	0.000054	0.0663	$\frac{\text{kg}}{\text{h}}$

Exhaust emissions for the analysed heating devices powered by different fuels are shown in Figure 5. The lowest CO₂ emissions were noted for a low-emission boiler (18 extract pipes) powered by beech and oak pellets. For O₂ emissions the lowest values were for the gas burner.

Biomass is characterized by a high content of total moisture (the total content of transient moisture and air-dry fuel moisture, calculated as a percentage in relation to the mass of working fuel). For fresh wood, the humidity is between 30 and 60%. For comparison, the moisture content of hard coal is generally between 2 and 12%, although wet coal can contain between 15 and 30% water, and in brown coal the moisture content can sometimes even exceed 35%. The calorific value of biomass depends on humidity. The calorific value of pine (the dominant species in Poland) is 17.8–16.1 MJ/kg in the air-dry state (at 15–25% humidity), and in the fresh state after cutting (at 80% humidity) –10.7 MJ/kg, and of hard coal –25 MJ/kg. Moisture is a disadvantage for a fuel, as it makes it difficult to ignite during combustion, contributes to the growth of the exhaust gases and lowers the calorific value, as can be seen in Figures 5 and 6.

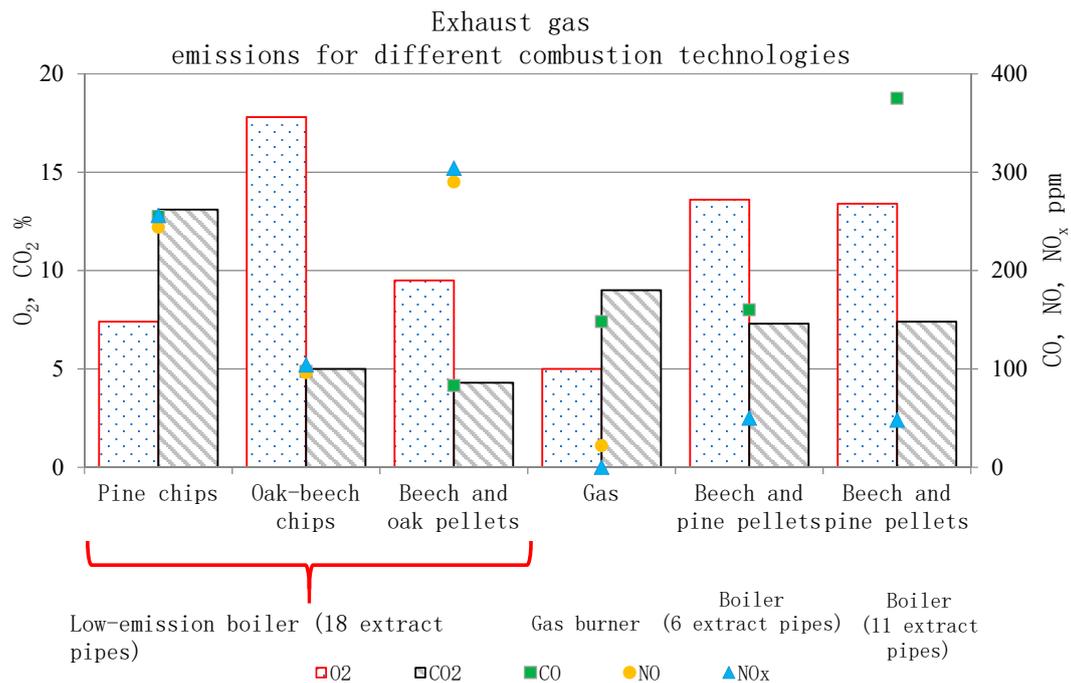


Figure 5. Comparison of exhaust gas emissions for the analysed heating devices powered by different fuels.

The highest combustion temperatures were recorded for a low-emission boiler (18 extract pipes) powered by: Pine chips (152 °C) and oak–beech chips (133.1 °C).

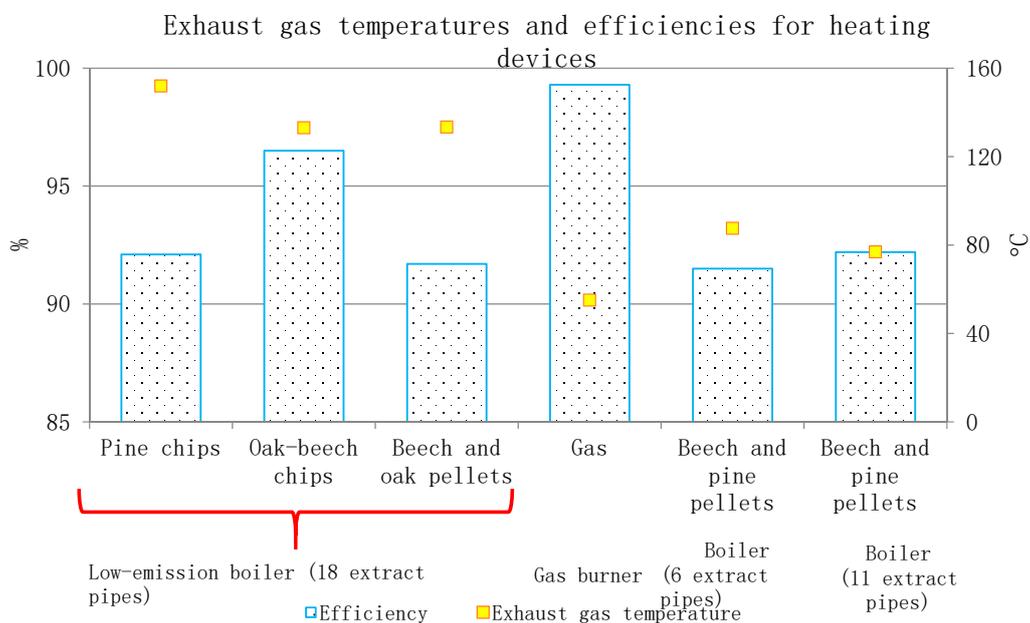


Figure 6. Comparison of exhaust gas emissions and efficiencies for the analysed heating devices powered by different fuels.

4.4. Discussion of Results

Every boiler, regardless of its type, emits pollutants into the atmosphere. The emission of pollutants depends on the design of the burner and the type of fuel burned. Low emissions are pollutants that enter the air at a height of less than 40 m. The main sources of low emissions are, among other things: Domestic solid fuel boilers and stoves, transport and small and medium industrial plants.

Comparison of the data from Table 3 indicates the main differences between both fuels, i.e., pine chips and beech and oak pellets. It can be seen that the pine chips contain much higher share of oxygen than carbon, while the share of oxygen in pellets is slightly lower than that of carbon. The share of hydrogen, as related to carbon, in pine chips is almost two times higher than that in beech and oak pellets. The content of remaining elements is negligible in both fuels. The effect of the mentioned differences of composition is visible also, as presented in Table 4, in the value of minimum oxygen demand. It is approximately double for pellets as for pine chips, which corresponds to the higher carbon content in pellets.

The data presented in Table 4 show substantial differences between emissions from the same fuels burned in different devices. As one may see, emissions from the proposed device are lower than from other burners. This indicates the evident effect of the new design. Emissions from lignite are also shown in Table 4. This clearly indicates the effect of the fuel of substantially different composition, showing the important characteristics of biomass-derived fuel.

Figures 5 and 6 visualize the data presented in the Table 6. For example, CO emissions from beech and oak chips and pellets in the low-emission boiler can be seen—18 extract pipes shows the value <100 ppm, which is even lower than when gas is burned in the other boilers; on the other hand, the pine chips show higher emission even when burned in the low emission burner. Consequently, the choice of biomass source and the form of the fuel play some role in the emissions observed.

Moreover, the thermodynamic efficiency of the system containing the boiler and particular fuel is high for the proposed low-emission boiler and oak–beech chips (only the gas burner reaches the higher value).

Important from the viewpoint of low-emissions environmental effects, and its influence on human health, is the content of dust in the emitted gases. As seen in Table 7 the lowest value is obtained for beech and oak pellets, slightly higher for pine chips and significantly higher for lignite.

One more remark can also be made, namely, whether or not it is worth using practically unprocessed fuel like pine chips. They show slightly worse emissions than pellets. One should consider, however, the energetic efficiency of the fuel's whole production process. As indicated in reference [108], the energetic efficiency of a complex process decreases with an increase of the number of subsequent sub-processes consuming energy. Therefore, the possibility of diminishing the number of individual production steps without lowering the final product (fuel) would assure a gain in efficiency.

5. Conclusions

The aim of the paper was to present the design of a new heating device for residential construction, and to analyze emissions in the case of burning biofuels. Based on the analysis, it can be concluded that:

- The thermodynamic efficiency of the proposed technical solution exceeds 92% and exceeds or at least equals the solutions available on the market;
- in the case of combustion of beech and oak pellets, the emission of CO₂, CO, O₂ in the proposed heating device was many times lower than the emission from devices available on the market;
- the emission of exhaust gases during the combustion of pine chips and beech and oak pellets is many times lower than the emission from lignite, which is important, especially in the context of countries where the energy mix is based on coal.

The municipal and housing sector largely affects the final emission of harmful substances, which is why it is so important to control and monitor the heating process of single-family houses. The proposed heating technology is inexpensive to use, it can use wood waste (chips, cuttings from sawmills or carpentry workshops) and, above all, it counteracts the occurrence of low emissions.

Author Contributions: Conceptualization, K.T. and J.W.; Methodology, O.O., L.M. and A.W.; Validation, A.Š., A.W. and K.T.; Investigation, O.O., L.M., A.W. and A.Š.; Writing—Original Draft Preparation, K.T., O.O. and J.W.; Funding Acquisition, A.Š. All authors have read and agreed to the published version of the manuscript.

Funding: The authors wish to express gratitude to Lublin University of Technology for financial support given to the present publication (Antoni Świć). The research was carried out under financial support obtained from the research subsidy of the Faculty of Engineering Management (WIZ) of Białystok University of Technology, from the grant No. WI/WIZ-INZ/4/2019 (Olga Orynych, Andrzej Wasiak) and Institute of Mechanical Engineering, Warsaw University of Life Sciences (Karol Tucki, Leszek Mieszkalski, Joanna Wichłacz).

Conflicts of Interest: The authors declare no conflict of interest.

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