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A Critical Investigation of Certificated Industrial Wood Pellet Combustion: Influence of Process Conditions on CO/CO_2 Emission

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Abstract: The pollutants emission into the atmosphere is largely related to human activity and health, whereas, of many factors, domestic heating systems greatly impact the emission rate. The measures taken to reduce the emission of harmful compounds to the atmosphere are slowly starting to bring the intended effects and a downward trend in emissions of such gases as carbon monoxide (CO), nitrogen oxides (NO_x), and sulfur dioxide (SO_2) is noticeable. The conducted tests allowed the determination of the combustion characteristics of individual pellet types available on the European market. During the tests, pellets were supplied to a 25 kW fixed-bed boiler with a constant mass flow of 3 $kg{\cdot}h^{-1}$, and the air-flow ratio was manipulated and presented in the form of the excess air coefficient λ (1.8–3.08). Pellets certificated with the ENPlus as A1 were found not meeting the requirements, mainly in the ash content, which negatively affected their combustion performance gradually and caused exceeded CO emissions up to 1000 $mg{\cdot}Nm^{-3}$. Pellets of declared lower classes were more beneficial for combustion in terms of emission factors.

Keywords: wood pellet; combustion; carbon monoxide emission; pellet certification

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1. Introduction

Biomass, the only form of renewable carbon source, receives increased interest as a fuel due to global green-energy trends triggered by the United Nations' announcement of the Sustainable Development Goals (SDGs) such as the 'Affordable and Clean Energy' and 'Climate Action'. Biomass is considered a zero-emission fuel due to the carbon cycle of plants that bond CO_2 during photosynthesis. While thermal treatment, perhaps combustion, the same amounts of carbon are released into the atmosphere. However, it is crucial to effectively carry out thermal processes to maximize the complete conversion of fuels and maximize the conversion of the fuel's chemical energy into heat and/or electricity.

Biomass used in home heating systems is in the form of wood and wood pellets, wood chips, wood briquettes, and firewood [1,2]. Compared to fossil fuels, biomass has a low C/H ratio and a high volatile matter content of up to 70% [3]. Moreover, biomass has a large share of volatile matter (65–80%) compared to coal, and its high reactivity causes the release of large amounts of volatile decomposition products in a short time [4]. About 80% of the fuel mass is degassed and burnt at 200–360 °C, while the remaining 20% burns at 360 °C to 490 °C [5]. Therefore, to burn large amounts of volatile products of biomass decomposition in low-power installations, constructions that meet the conditions of complete combustion are used, mostly having two chambers: degassing and combustion of degassing products [6]. The size of fuel particles also has great importance during biomass combustion. Smaller fuel particles allow for more effective contact with the oxidizing agent (air), resulting in fewer incomplete combustion products, such as carbon monoxide, being emitted during combustion. Moreover, smaller particles are beneficial due to faster ignition and a more stable combustion process [7]. On the other hand, too small a particle size might trigger the explosion possibilities during combustion [8].

Wood pellets are one of the most commonly used fuels in household heating installations. The growing popularity of pellets is triggered by (i) the recommendations of the European Union to prevent using coal as a main solid fuel in central heating units, (ii) the high availability of combustors (boilers) automatically fed by pellets, and (iii) the governmental financial support to implement them for induvial and small-scale use (boilers below 500 kW of power capacity). Additionally, wood biomass is the most available, which plays a crucial role in climate change mitigation and circular economy development [9]. Moreover, the ecological awareness of European society, built through education, promotes the use of clean and renewable pellets as a fuel [10,11]. According to the European Pellet Council (EPC) data, in 2018, the production of pellets in Europe amounted to 20.1 million tonnes, of which the EU countries produced over 16.9 million tonnes [12]. It has to be emphasized that wood pellets are always produced from wood waste, and therefore their thermal utilization does not compete with wood processed for the construction sector [13].

In order to ensure the quality of available solid biofuels, these certification standards have been introduced as the norms: pan-European EN ISO 17225-2:2021, Austrian ÖNORM M 7135, or the German DIN 51731 [14–16]. Based on the EN ISO 17225 [17] norm, the ENplus certificate is controlled by the European Pellet Association and divides pellets into three main classes: A1, A2, and B. The classes distinguish pellets of different quality; for instance, class A1 allows ash content in a dry state up to 0.7%, and for class A2, it is up to 1.5%. Mostly used in industrial units, B pellets can have up to 3% ashes. Pellet certification is prestigious and voluntary. Some pellet producers are willing to promote their high-quality products using only the EN Plus certificate, while others also decide to obtain the DINPlus certificate. However, a recent study [18] describing the certificated pellet quality outlines discrepancies between the declared producers' quality and the actual quality of the products sold. This raises an important question on the combustion performance of certificated pellets. Many process factors might affect the combustion parameters, such as the boilers' power capacity, airflow, and fuel flow characteristics. Vicente et al. [19] evaluated the combustion performance of industrial A1 pellets in a small-scale boiler (9.6 kW) and found that the fuel properties given by the producer do not always ensure the regarded quality. The performed study describes the pellet combustion depending on the set boiler power, which is important for the combustion unit operator. However, in order to further investigate the emission rate, additional input data have to be evaluated, for instance, the air excess ratio (λ) and its effect on the CO_2 and CO emissions. The mentioned gases are an indicator of effective combustion; therefore, their emission was investigated in the current study for testing the pellets' quality combustion.

The work aimed to analyze the combustion performance of certificated wood pellets available on the European market in terms of CO_2 and CO emissions. During the study, pellets of the A1, A2, and B classes were combusted in a fixed-bed rotary grate boiler with a power capacity of 25kW, which is one of the most popular used units supplied by pellets.

2. Materials and Methods

2.1. Feedstocks

The research material consisted of 4 types of pellets available on the European market. Tested pellets were selected as the easiest to reach (most popular) in the area of Białystok, Poland. The fuels were purchased in original commercial packaging weighing 15 kg. In the case of fuels marked as P1 and P2, the packaging contained information such as the manufacturer's name and address, basic fuel parameters as well as logotypes, and names of certificates. Granulates marked as P3 and P4 had basic information on the fuel parameters on the packaging, and they were also marked by the manufacturer as meeting the class A2 (P3) and B (P4) (Table 1).

Table 1. Quality classification of tested pellets and their selected properties according to ISO 17225-2:2014.

Parameter \ Sample	P1	P2	P3	P4
Certification	Yes	Yes	No (producers' declaration)	No (producers' declaration)
Quality class	A1	A1	A2	B
Diameter [mm]	6			
Moisture content [wt%]	≤10			
Ash content [wt%]	≤0.7		≤1.5	≤3.0
Mechanical durability [%]	≥97.5			≥96.5
Lower heating value [MJ·kg^{-1}]	16.5 ≤ LHV ≤ 19		16.3 ≤ LHV ≤ 19	16.0 ≤ LHV ≤ 19
Nitrogen content [wt%]	≤0.3		≤0.5	≤1.0
Sulfur content [wt%]	≤0.03			≤0.04
Chlorine content [wt%]	≤0.02			≤0.03

2.2. Pellets Characterization

The morphology of pellets has been observed using a digital microscope, Keyence VHX-7000 (Keyence, Osaka, Japan). The observations have been conducted with various magnifications (from 50× to 500×).

The tested pellets were analyzed analytically to evaluate their basic properties as total moisture content according to ISO 18134:2017 with a moisture analyzer with an accuracy of 0.01%. The measurement was repeated three times for each sample. Furthermore, the analytical moisture content, volatile content, and ash content were determined using a thermobalance TG 209 F1 Libra-NETZSCH, following the requirements of ISO18134:2017, ISO18123:2016, and ISO18122:2016, respectively. The fixed carbon content was calculated by subtracting from 100% the analytical moisture content, ash content, and volatiles content.

The higher heating value (HHV) of pellets was determined using a bomb calorimeter KL-12Mn by Precyzja-Bit (Poland) in accordance with the ISO 1928:2002 standard. The lower heating value (LHV) was calculated as follows:

$$\mathrm{LHV} = \mathrm{HHV} - 24.43 \cdot \left(\mathrm{MC} + 8.94\mathrm{H}^{a}\right) \quad \left[\mathrm{KJ} \cdot \mathrm{kg}^{-1}\right] \tag{1}$$

where MC is the moisture content [wt%], H^a is the hydrogen content [wt%] assumed as 6 wt%, 24.23 is the coefficient taking into account the heat of vaporization of water at 25 °C corresponding to 1% of water in the fuel, and 8.94 is the coefficient resulting from the stoichiometry of the hydrogen combustion reaction (occurring quantitative transformations).

The presented results of analytical tests represent the average of three repetitions.

2.3. Combustion Analysis

The combustion process was conducted at a laboratory setup consisting of a fixed-bed rotary furnace (Moderator, Hajnówka, Poland) with a power capacity of 25 kW (Figure 1). Tests were performed during the winter of 2021–2022. The boiler was designed with the technology of upper combustion, where the exhaust leaves the chamber without passing through the fuel bed. Before starting the test, the boiler was heated for 1 h to obtain stable combustion conditions and a boiler temperature of ca. 70 °C.

The feedstocks were fed periodically to the combustion chamber by an automatic feeder. The fuel flow has been fixed for all tests at a value of 3 kg·h^{-1}. The combustion of pellets took place in variable conditions of the airflow into the combustion chamber. The boiler controller enables setting the air fan efficiency value in percentages; therefore, settings of 20, 22, 24, and 26% were used in this study. These amounts are uncountable in relation to mass flow or air volume (there is no flowmeter installed at the setup). Hence, the analysis of gas concentration was made in terms of the calculated excess air coefficient λ:

$$\lambda = \frac{21.5}{21.5 - O_2'} \quad [-] \tag{2}$$

where O_2' is the oxygen concentration in the exhaust [vol%].

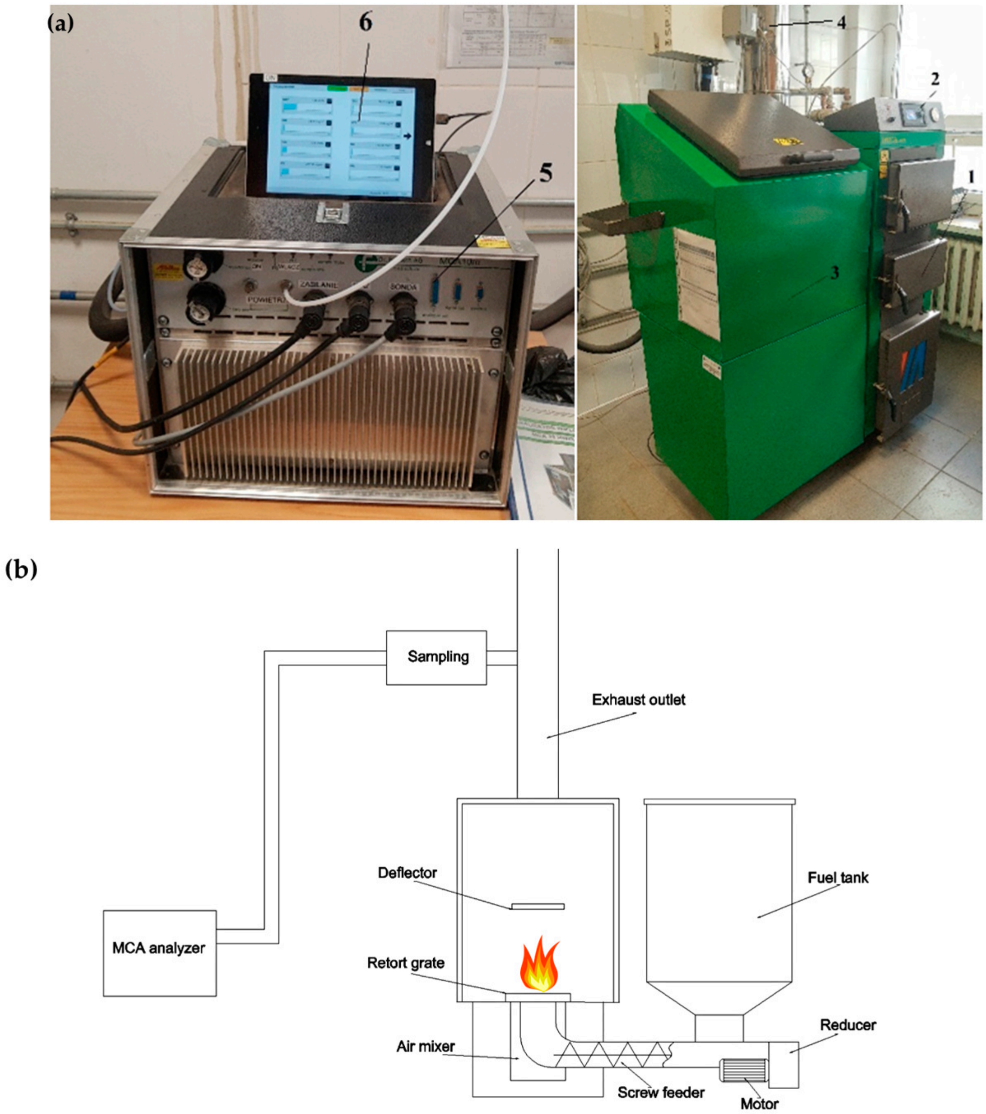

Figure 1. Laboratory combustion setup: (**a**) 1—Unica VentoEko boiler (Moderator, Poland), 2—boiler controller, 3—fuel tank, 4—exhaust gas sampling point, 5—MCA10 analyzer, 6—tablet for archiving measurements (authors' graphs), and (**b**) scheme of the setup (authors' graphs).

The exhaust was collected at (4) ca. 1.5 m above the boiler's grate and analyzed for carbon monoxide (CO), carbon dioxide (CO_2), and oxygen (O_2) content using the MCA10 analyzer (5) with a sampling period of 20 s. The result was displayed on a tablet (6). The principle of operation of the analyzer is based on the recognition of gas components in the infrared. The additionally installed cell with zirconium dioxide makes it possible to measure the molecular oxygen content in the exhaust gas. CO_2 and O_2 content are given by the analyzer in percent, CO in $mg \cdot m^{-3}$.

The obtained amount of CO_2 and CO in the exhaust was normalized to a 10% content of O_2 as follows:

$$N = \frac{21 - O_2''}{21 - O_2'} \cdot M \quad (3)$$

where N is the calculated gas content [%, $mg \cdot m^{-3}$], M is the obtained gas content [%, $mg \cdot m^{-3}$], O_2'' is the requited oxygen content = 10% [%], and O_2' is the obtained oxygen content [%]

Furthermore, ashes from each sample were collected, and their carbon content was investigated using a Shimadzu TOC (Kyoto, Japan) carbon analyzer. The methodology consisted of high-temperature oxy-combustion (900 °C) coupled with IR detection. The carbon content was also investigated for each pellet type, and the carbon conversion ratio (C_{conv}) has been calculated:

$$C_{conv} = \left(1 - \frac{C_{ash}}{C_{pellets}}\right) \cdot 100\% \quad (4)$$

where C_{ash} is the carbon content in ashes [%] and $C_{pellets}$ is the carbon content in pellets [%]

3. Results and Discussion

3.1. Pellets' Characteristics

Table 2 presents the proximate analysis of pellets, their calorific values (HHV and LHV), and the carbon content of each sample.

Table 2. Properties of the tested pellets (as received).

Property \ Sample	P1	P2	P3	P4
Pellet certification	A1	A1	A2 [1]	B [1]
Total moisture content [wt%]	6.57 ± 0.12	3.72 ± 0.14	7.09 ± 0.09	4.64 ± 0.17
Analytical moisture content [wt%]	2.63 ± 0.02	2.34 ± 0.02	2.53 ± 0.05	2.32b ± 0.06
Volatile content [wt%]	77.30 ± 0.09	79.44 ± 0.05	75.00 ± 0.16	75.85 ± 0.34
Ash content [wt%]	5.26 ± 0.11	1.71 ± 0.03	6.11 ± 0.35	2.40 ± 0.19
Fixed carbon content [wt%]	14.81	16.51	16.29	19.43
Total carbon content [wt%]	62.83 ± 1.30	61.38 ± 0.94	62.14 ± 0.43	66.44 ± 0.56
Total organic carbon content [wt%]	60.19	56.98	58.03	55.06
HHV [MJ·kg^{-1}]	22.13 ± 0.16	21.82 ± 0.15	21.32 ± 0.16	21.26 ± 0.17
LHV [MJ·kg^{-1}]	20.70	20.34	19.77	19.76

[1] declared by the producer.

P1 and P2 pellets represented the A1 certificate; however, their properties vary meaningfully in the case of ash content, and both do not meet the requirements of ash content below 0.7 wt%. [17]. The certificated ash content was only kept by the P4 (B) pellets, where the highest carbon content was obtained. The incompatibility of pellet parameters and the certification requirements was also confirmed in other studies [19].

The higher carbon content of P1 than P2 (1.5% higher) resulted in a higher HHV and LHV. However, the P2 pellets were found to have a fixed carbon content ca. 2% higher; therefore, their combustion should be slightly longer in time than P1.

For each pellet sample, the total carbon and the total organic carbon were tested. Here, a big difference of more than 10% in these two values was observed for P4 pellets. This observation might indicate some nonorganic carbon-rich materials being added to the pelletized feedstock. For instance, materials include plastics such as polypropylene, polyethylene or polystyrene, or residual sawdust from the furniture industry. These additions will not necessarily be detected during combustion if only the basic exhaust composition (CO_2, CO, and O_2) is being investigated. However, it has to be emphasized that inorganic additions to fuel pellets are banned on the polish market, and this data indicates that more precise quality controls should be provided. Dishonest producers are adding the abovementioned nonorganic materials to pellets to boost their calorific values, which will directly affect the increase in their combustion temperature [20], and will result in a positive energy effect for the boiler user. On the other hand, the added materials might have unknown additives, which might be decomposed into environmentally harmful substances during combustion.

The surface of the pellets is shown in Figures 2 and 3. The obtained images clearly show the compact structure of the pellets. Nevertheless, the individual petals may be noticed.

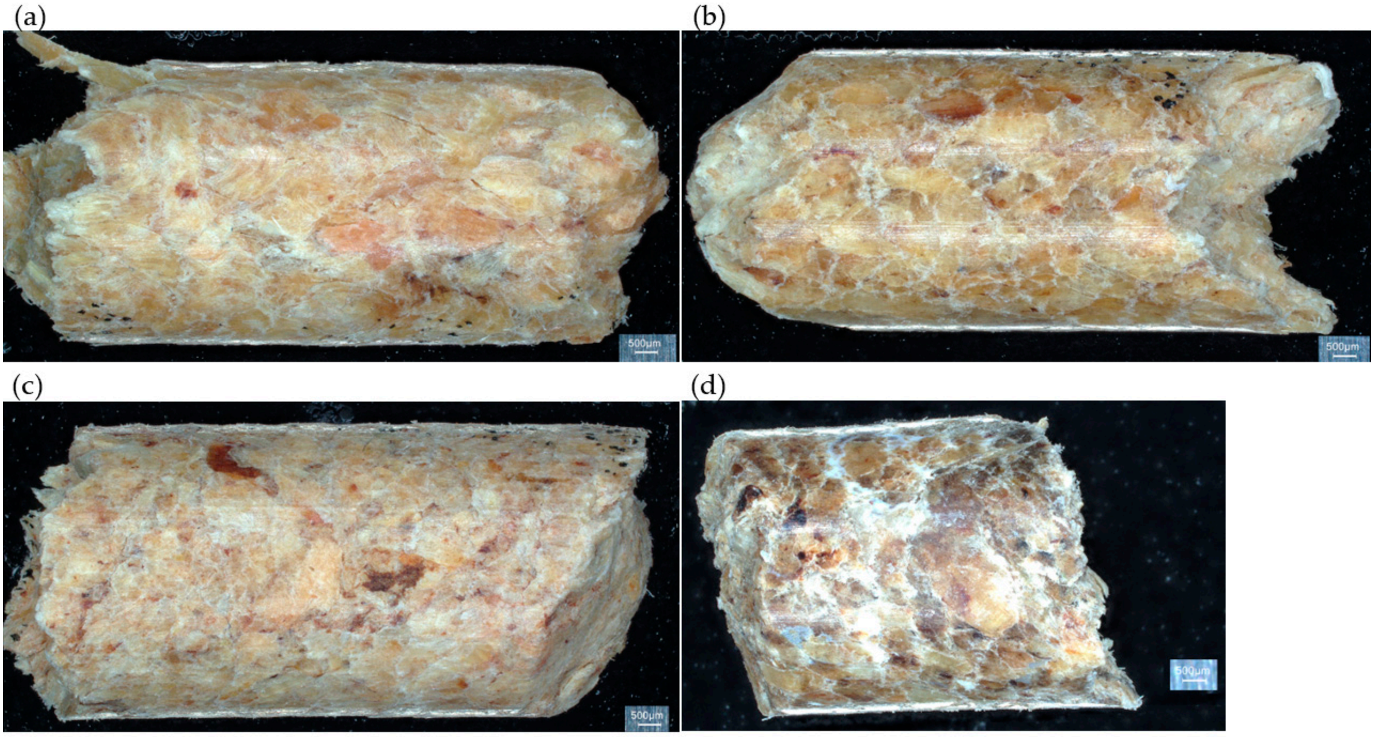

Figure 2. Structure and surface area of tested pellets (**a**) P1, (**b**) P2, (**c**) P3, and (**d**) P4.

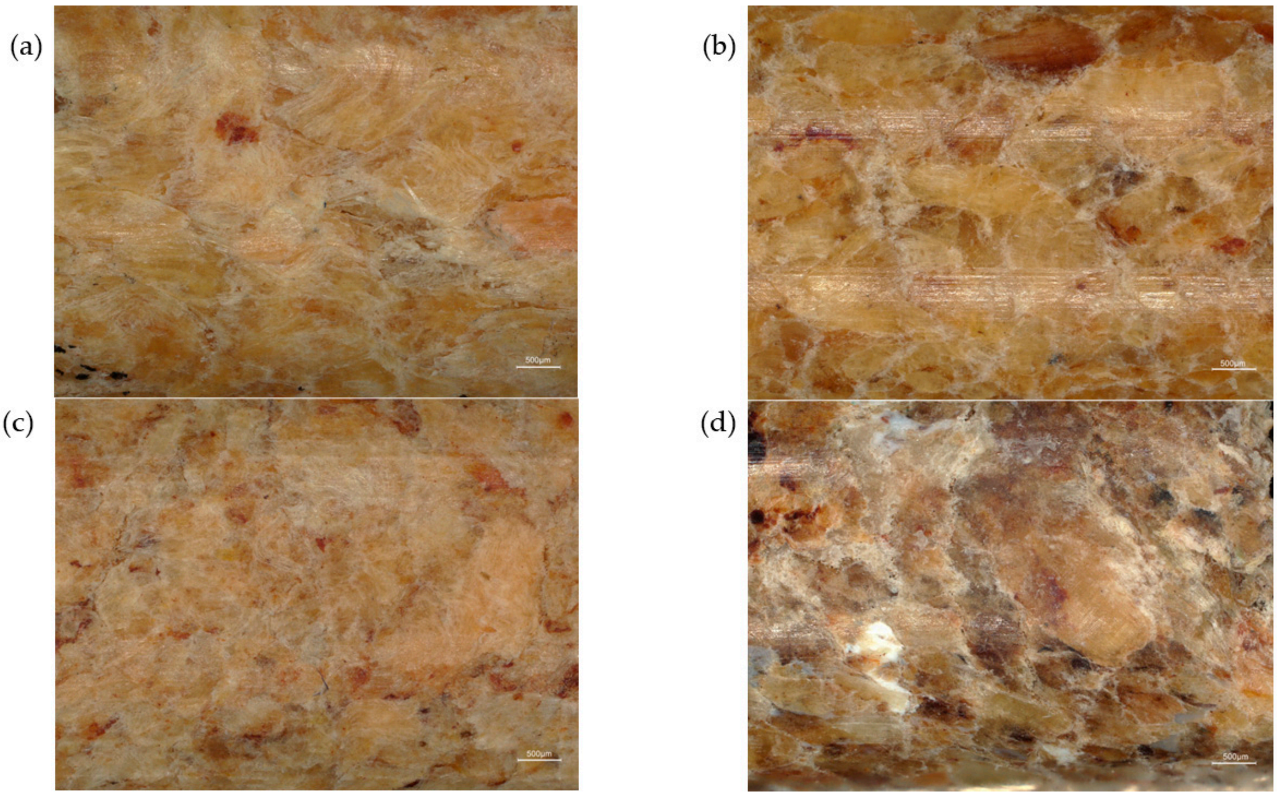

Figure 3. Surface area of tested wood pellets (**a**) P1, (**b**) P2, (**c**) P3, and (**d**) P4.

Figures 2 and 3 clearly show the differences between the tested pellets in terms of their structure, surface area, and color. The shiny surface area characterizes pellets P1, P2, and P4. This property is considered for consumers as an indicator of the pellets' quality and is usually obtained for feedstocks compacted at high pressures and ideal moisture content. Therefore they reach high-density parameters (bulk density above 600 kg·m^{-3}) and high mechanical durability (above 98%).

Compared to the other pellets, the P4 pellets have a smaller length and a visibly darker color, which may be another factor indicating that nonorganic materials were added to the pelletized material. On the other hand, the color might also be a result of using lower-quality wood (containing tree bark) as a feedstock [18].

3.2. Combustion of Pellets

3.2.1. Airflow Characteristics and Combustion Efficiency

The relation between the set airflow (20, 22, 24, and 26%) during combustion was correlated with the excess air coefficient λ and shown in Figure 4 and Table 3. The obtained high R^2 values indicate a strong linear trend between the set airflow and calculated values (λ) and proof the reliability of further considerations.

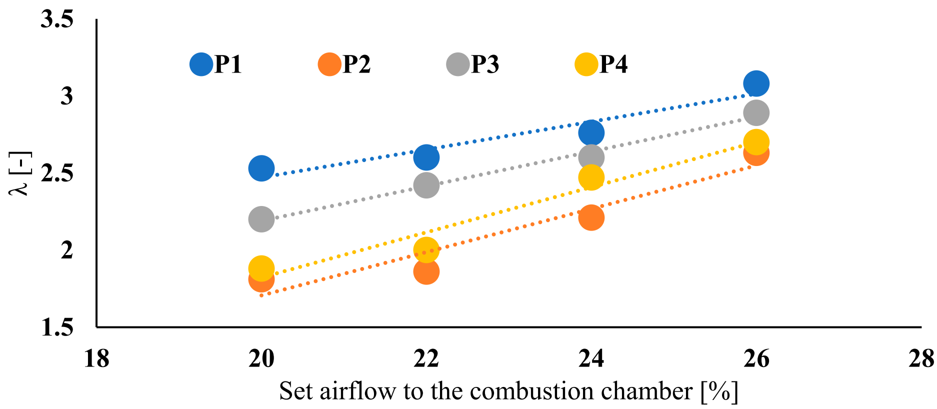

Figure 4. Correlation between the set airflow during combustion and the calculated λ coefficient.

Table 3. Linear regression and correlation factors of the excess air coefficient and the set value of airflow.

Sample	Linear Equation	R^2
P1	λ = 0.0905x + 0.0661	0.91
P2	λ = 0.1405x − 1.104	0.91
P3	λ = 0.1125x − 0.06	0.99
P4	λ = 0.1465x − 1.107	0.95

x—the set value of airflow during combustion.

The **λ** coefficient illustrates the contact of the combusted particle with the oxidizing agent (the higher it is, the worse the contact), where λ = 1 state for stoichiometric combustion. The best contact with the oxidizing agent was obtained for P2 (1.81) and the worst for pellet P1 (3.08) (Figure 4). However, both pellets were classified by the producers as A1-certificated products. This phenomenon correlates with the feedstocks' ash content (Table 3), the P1 was found to have ca. 6% of the mineral matter, and the P2 ash content was below 2 wt%. The P3 (A2 certificate) ash content was at a similar level to P1, as well as the values of λ (Figure 5).

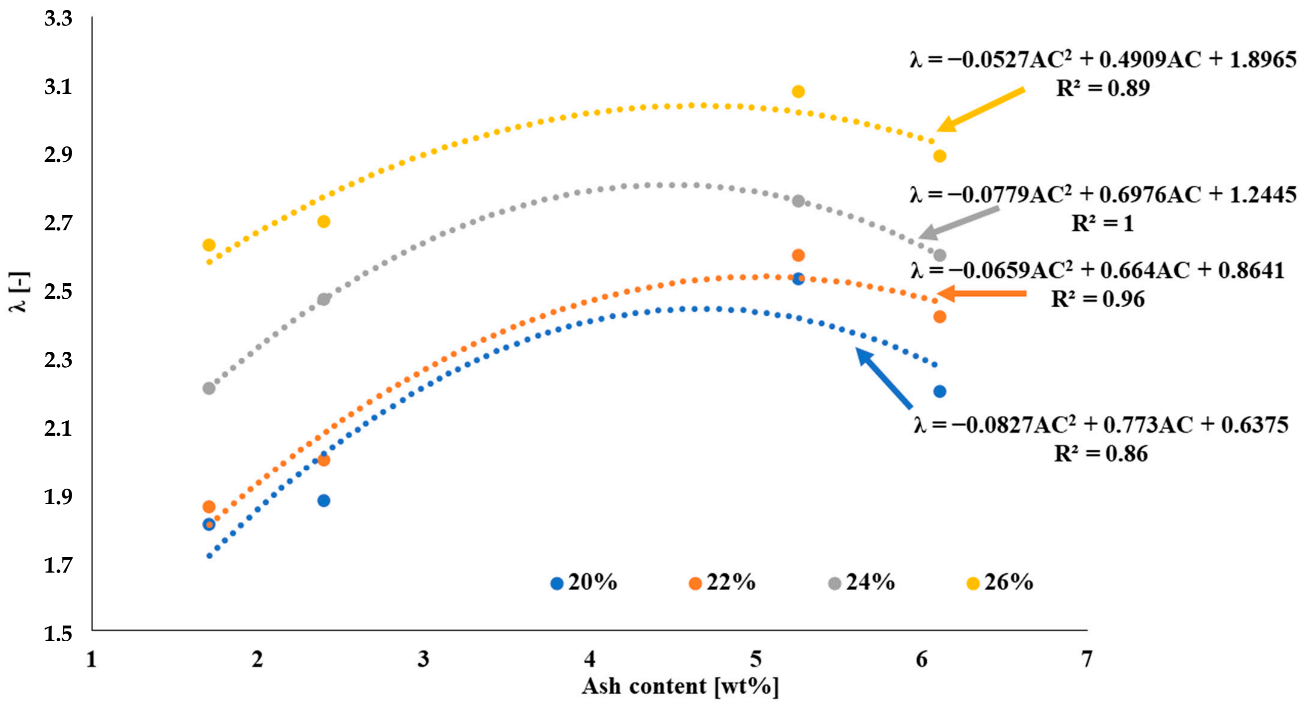

Figure 5. Dependence of the excess air coefficient λ from the fuel ash content (AC).

The efficiency of combustion can be represented by the carbon conversion ratio. The not oxidized carbon remains in ashes; therefore, the energy of this reaction can be considered lost during the process. Table 4 represents the calculated carbon conversion factor (C_{conv}) given as the percentage of carbon being oxidized during combustion. The combustion efficiency of P1 and P2 pellets is found to be strongly affected by the air coefficient. For instance, a λ increase from 2.53 to 3.08 resulted in a 9% increase in the C_{conv} of P1 pellets. This phenomenon can be associated with the high ash content of P1 and consequently limits the contact of combustibles and air. Moreover, an increase in the air supply to the combustion chamber also results in higher pressures, which can more precisely penetrate the fuel particles improving oxidation.

Table 4. Combustion efficiency represented by carbon conversion.

Pellet Type	Airflow [%]	λ [-]	Total Carbon in Ash [wt%]	C_{conv} [%]
P1	20	2.53	16.21	74.20
	22	2.6	12.53	80.06
	24	2.76	11.58	81.57
	26	3.08	10.44	83.38
P2	20	1.81	11.67	80.99
	22	1.86	9.82	84.00
	24	2.21	10.13	83.50
	26	2.63	8.13	86.75
P3	20	2.2	9.44	84.81
	22	2.42	9.98	83.94
	24	2.6	9.15	85.28
	26	2.89	8.62	86.13
P4	20	1.88	7.06	89.37
	22	2	6.98	89.49
	24	2.47	7.07	89.36
	26	2.7	6.73	89.87

Pellets P3 and P4 were not meaningfully affected by the increasing λ.

3.2.2. Emissions of CO_2 and CO

Figure 6 represents the emission of CO_2 during pellet combustion in different air-flow conditions represented by the λ coefficient. The CO_2 emissions from combustion are not regulated. However, the obtained values are at levels common for wood pellet combustion in same-scale boilers [20]. The increase in the λ each time triggered the increase in CO_2 emissions, where the trend was especially strong for P2 and P3 pellets.

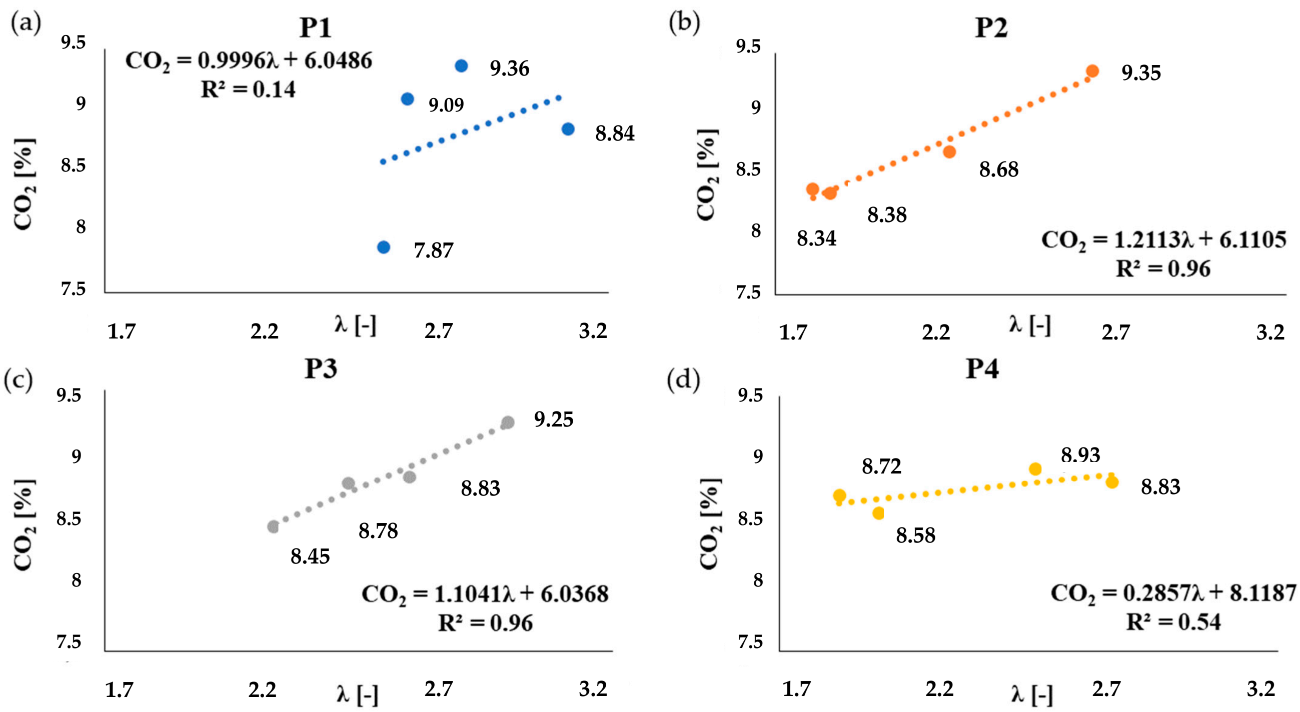

Figure 6. Emission of CO_2 during pellet combustion in dependence on the air supplied to the combustion chamber (**a**) P1, (**b**) P2, (**c**) P3, (**d**) P4.

Carbon monoxide, the product of incomplete combustion, is limited to an amount of 500 mg per 1 m^3 of exhaust at 10% oxygen content by the European Ecodesign Directive [21]. The content of CO during performed tests is shown in Figure 7 in dependence on the λ value. The CO content during the combustion of the tested pellets differs significantly at the lowest airflow values. Pellets P1 and P2 show (both A1) were found to exceed the Ecodesign limits when the λ was at its lowest value. Further increasing of the airflow resulted in a decrease in CO content (Figure 7) and an increase in CO_2 (Figure 6), which proves that the equilibrium of the oxidation reaction has shifted towards CO_2.

Venturini et al. [22] state that lower-quality pellets are more likely to cause high emissions of harmful substances such as CO or PAH (polycyclic aromatic hydrocarbons). The quality of pellets might be affected by additional interjections such as bark and branches. Moreover, the pellet size also impacts on its combustion properties, where larger particles combust less effectively due to limited surface area [23].

Nevertheless, the combustion behavior of tested pellets was affected by various factors and required an individual approach in each case. Due to this, Figures 6–8 were prepared and presented to outline (i) the disparity between pellets of the same certification (P1 and P2) and (ii) the differences between each pellet class.

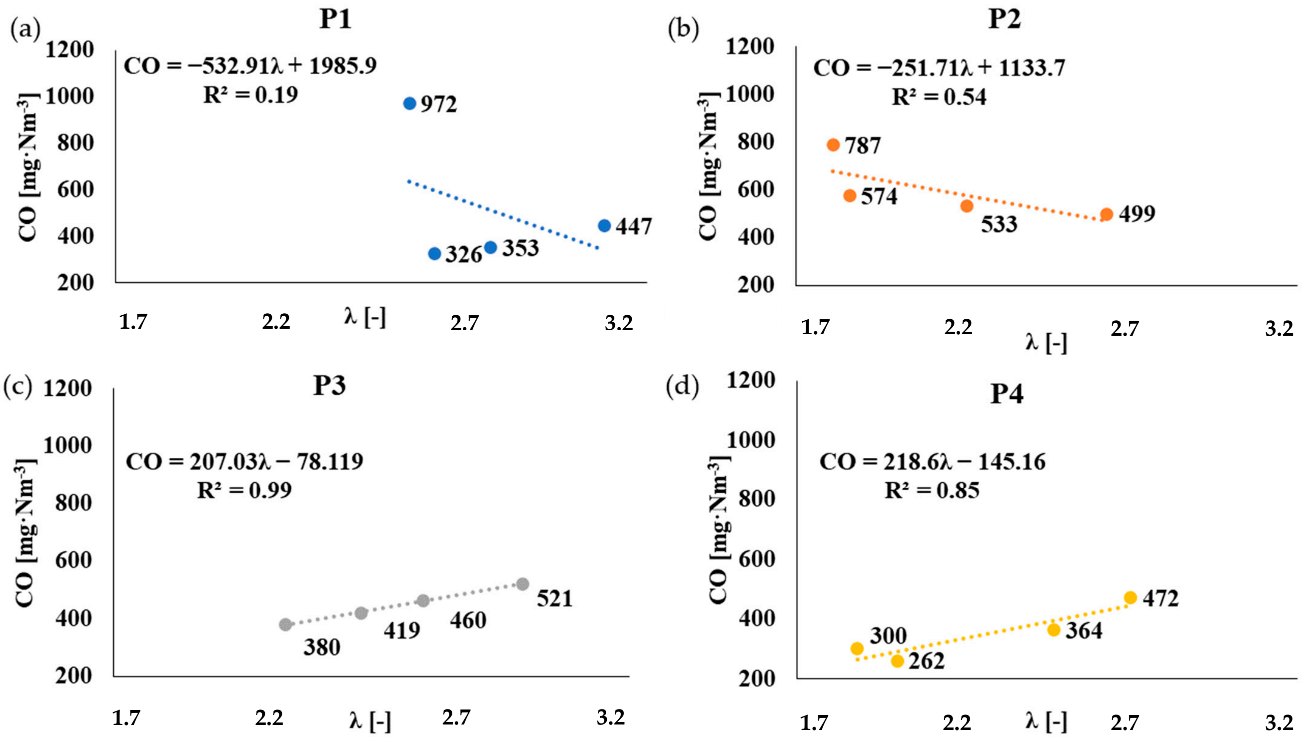

Figure 7. Emission of CO during pellet combustion in dependence on the air supplied to the combustion chamber (**a**) P1, (**b**) P2, (**c**) P3, and (**d**) P4.

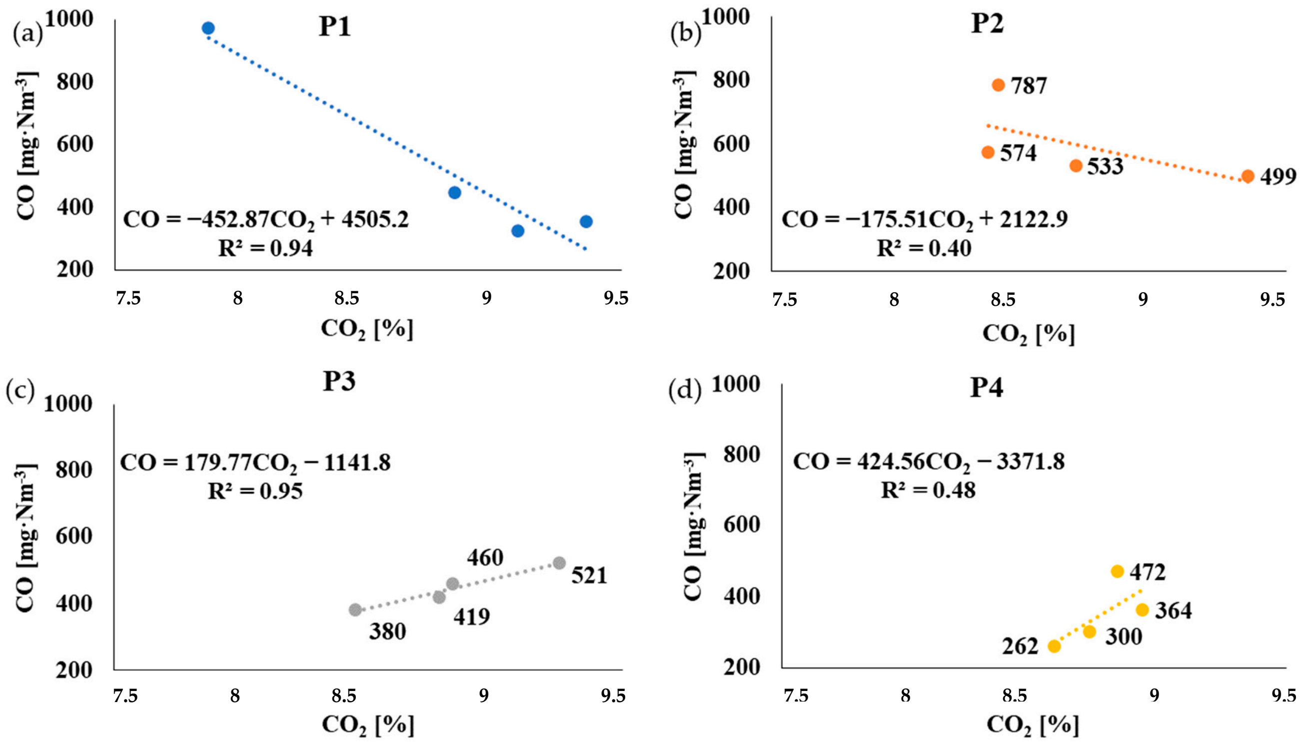

Figure 8. Correlations between CO_2 and CO emissions during pellet combustion (**a**) P1, (**b**) P2, (**c**) P3, and (**d**) P4.

Pellets P1 are found to be premium-class biofuels meeting the strictest quality requirements. However, the ash content was found here to be more than five times exceeding the limits, consequently affecting the combustion performance [24]. Limited contact of the combustibles with oxygen resulted in high contents of CO (ca. 1000 mg·Nm^{-3}) during low airflow conditions. Furthermore, increased air intake gradually caused a decrease in the CO content in the exhaust, favoring the formation of CO_2 (Figure 8). However, a similar slighter phenomenon was observed for pellets P2, where the low airflow ratios resulted in exceeded CO shares in the exhaust. Hypothetically, in the case of P2, the increased emission values can be explained by the use of biomass by producers in the form of, e.g., bark [25], as Figures 2 and 3 show dark inclusions in the pellet structure.

The tested pellets representing class A1 were characterized by the least favorable emission properties among all samples. This observation underscores the need for more thorough and stringent controls in units producing certified pellets.

Regarding the correlation factors (R^2), the most affected by the airflow conditions was the pellet marked P3 (A2 class as declared by the producer). The increase in airflow resulted in an increase in CO_2 content from 8.45% up to 9.25% and the CO content from 380 to 520 mg·Nm^{-3}. Only pellets P4 were found not to exceed the CO emission norms apart from the airflow supplied to the combustion chamber. However, P4 pellets are most probably enriched with nonorganic additives (Table 2, Figures 2 and 3), which are meant to increase the calorific value of the fuel and lower its production costs by 'filling-in' the pellet structure and possibly also lowering the energy consumption of pelletization (lubricant effect).

It is significantly visible that the tested pellets can be divided into two groups based on the emission factors (Figures 7 and 8). First, where the increase in λ leads to a drop in CO formation—pellets P1 and P2 (certificated A1), and where during the λ elevation, the CO content in exhaust also increases—pellets P3 and P4 (declared as A2 and B, representatively). Moreover, for pellets P2 and P3, the carbon conversion C_{conv} (Table 4) was less affected by the rising λ. Therefore, it can be stated that these fuels do not require high values of airflow for combustion, and a rise in the air blow might have even a negative effect by indicating faster and less effective oxidation of carbon (higher share of CO in the exhaust).

The obtained results confirm previous studies of Vicente et al. [19] that the certification of pellets does not ensure their combustion performance. The mentioned authors evaluated, among others, the CO share in the flue gases and concluded that noncertificated pellets met the emission requirements (CO below 200 mg·Nm^{-3}). However, the A1 samples reached emissions of even above 700 mg·Nm^{-3} at medium boiler power. The boiler power was set by an automatic controller. Therefore, reaching higher operating power probably increased the fuel intake and the air amount supplied to the combustion chamber. These two variables simultaneously affected the emission rate, which is highly important for modeling the correct boiler settings at low-power units. In the current study, the fixed feedstock flow allowed for investigating the air-flow effect on pellet combustion. Therefore, it is seen that the higher amount of O_2 during the combustion of certificated pellets resulted in a decrease in CO content in the exhaust and favored the creation of CO_2 (Figure 8).

4. Conclusions

The study aimed to determine the impact of process conditions on CO and CO_2 emissions during the combustion of different classes of wood pellets. Using a low-emission boiler that meets the latest emission standards (Ecodesign), variable process conditions, and different fuel types made it possible to determine the impact of these parameters on the emission of CO and CO_2 during the combustion of solid fuels into the atmosphere. During the combustion tests, a decrease in CO emissions was observed with a simultaneous increase in CO_2 content in the exhaust gases. The obtained results confirm that the number of pollutants generated during combustion and their type depends on the type of fuel burned and process factors such as air-blowing power.

Pellets with certificates class A1, i.e., P1 and P2, are characterized by different contents of CO_2 and CO (200 mg·$^{-3}$ difference at the lowest air-flow rate) in the exhaust. Moreover, it was found that the certificated biomass pellets exceed by almost 500 mg·$^{-3}$ the required CO emissions, which greatly affects their combustion performance. Two tested A1 pellets significantly exceeded the declared quality ($\leq$0.7%) by showing a high ash content of

5.26 and 1.71%. The pellet type evaluated as an example of a B certificate was found to have nonorganic additives that might lower the production cost. However, the unknown chemical composition may have a destructive effect on the environment.

Reducing the emission of pollutants and, consequently, striving to improve air quality affects the constant promotion of the use and improvement of low-emission fuel combustion technologies. Thus, low-emission heating structures and proven fuels that meet the latest emission standards and do not contain additives that may negatively impact the boiler structure and the environment should be used. Optimizing process conditions for a given fuel can affect the amount of energy obtained from combustion and significantly reduce the emission of harmful substances into the atmosphere. This issue is important and is part of the actions counteracting climate change.

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References

1. Roy, M.M.; Corscadden, K.W. An experimental study of combustion and emissions of biomass briquettes in a domestic wood stove. *Appl. Energy* **2012**, *99*, 206–212. [CrossRef]
2. Bogoslavska, O.; Stanytsina, V.; Artemchuk, V.; Garmata, O.; Lavrinenko, V. Comparative Efficiency Assessment of Using Biofuels in Heat Supply Systems by Levelized Cost of Heat into Account Environmental Taxes. In *Systems, Decision and Control in Energy II. Studies in Systems, Decision and Control*; Zaporozhets, A., Artemchuk, V., Eds.; Springer: Cham, Switzerland, 2021; Volume 346. [CrossRef]
3. Khan, A.A.; de Jong, W.; Jansens, P.J.; Spliethoff, H. Biomass combustion in fluidized bed boilers: Potential problems and remedies. *Fuel Process. Technol.* **2009**, *90*, 21–50. [CrossRef]
4. Wang, C.; Zhu, X.; Liu, X.; Lv, Q.; Zhao, L.; Che, D. Correlations of chemical properties of high-alkali solid fuels: A comparative study between Zhundong coal and biomass. *Fuel* **2018**, *211*, 629–637. [CrossRef]
5. Ryu, C.; Bin Yang, Y.; Khor, A.; Yates, N.E.; Sharifi, V.N.; Swithenbank, J. Effect of fuel properties on biomass combustion: Part, I. Experiments—Fuel type, equivalence ratio and particle size. *Fuel* **2006**, *85*, 7–8, 1039–1046. [CrossRef]
6. Kijo-Kleczkowska, A.; Szumera, M.; Gnatowski, A.; Sadkowski, D. Comparative thermal analysis of coal fuels, biomass, fly ash and polyamide. *Energy* **2022**, *258*, 124840. [CrossRef]
7. Yang, Y.B.; Ryu, C.; Khor, A.; Sharifi, V.N.; Swithenbank, J. Fuel size effect on pinewood combustion in a packed bed. *Fuel* **2005**, *84*, 2026–2038. [CrossRef]
8. Zhao, J.P.; Tang, G.F.; Wang, Y.W.; Han, Y. Explosive property and combustion kinetics of grain dust with different particle sizes. *Heliyon* **2020**, *6*, 1–7. [CrossRef] [PubMed]
9. Lee, Y.-R.; Tsai, W.-T. Overview of Biomass-to-Energy Supply and Promotion Policy in Taiwan. *Energies* **2022**, *15*, 6576. [CrossRef]
10. Niedziółka, I.; Kachel-Jakubowska, M.; Kraszkiewicz, A.; Szpryngiel, M. Analysis of Physical Properties of Plant Biomass Briquettes. *Agric. Eng.* **2013**, *2*, 233–243. Available online: https://yadda.icm.edu.pl/baztech/element/bwmeta1.element.baztech-07455f7f-f02a-4cfb-90c4-66234d83d036 (accessed on 20 September 2022). (In Polish)
11. Nižetić, S.; Papadopoulos, A.; Radica, G.; Zanki, V.; Arıcı, M. Using pellet fuels for residential heating: A field study on its efficiency and the users' satisfaction. *Energy Build.* **2019**, *184*, 193–204. [CrossRef]
12. European Pellet Council, Bioenergy Europe's Statistical Report 2019. Available online: https://epc.bioenergyeurope.org/about-pellets/pellets-statistics/ (accessed on 1 September 2022).
13. Zbieć, M.; Franc-Dąbrowska, J.; Drejerska, N. Wood Waste Management in Europe through the Lens of the Circular Bioeconomy. *Energies* **2022**, *15*, 4352. [CrossRef]
14. Shen, H.; Luo, Z.; Xiong, R.; Liu, X.; Zhang, L.; Li, Y.; Du, W.; Chen, Y.; Cheng, H.; Shen, G.; et al. A critical review of pollutant emission factors from fuel combustion in home stoves. *Environ. Int.* **2021**, *157*, 106841. [CrossRef] [PubMed]
15. Paredes-Sánchez, J.P.; López-Ochoa, L.M. Bioenergy as an Alternative to Fossil Fuels in Thermal Systems. In *Advances in Sustainable Energy*; Lecture Notes in Energy; Vasel, A., Ting, D.K., Eds.; Springer: Cham, Switzerland, 2019; Volume 70. [CrossRef]

16. Christoforou, E.; Fokaides, P.A. Solid Biofuels Thermochemical Conversion: Combustion for Power and Heat. In *Advances in Solid Biofuels. Green Energy and Technology*; Springer: Cham, Switzerland, 2019. [CrossRef]
17. *ISO 17225-1:2021*; Solid Biofuels—Fuel Specifications and Classes—Part 1: General Requirements. ISO: Geneva, Switzerland, 2021.
18. Kamperidou, V. Quality Analysis of Commercially Available Wood Pellets and Correlations between Pellets Characteristics. *Energies* **2022**, *15*, 2865. [CrossRef]
19. Vicente, E.D.; Vicente, A.M.; Evtyugina, M.; Tarelho, L.A.C.; Almeida, S.M.; Alves, C. Emissions from residential combustion of certified and uncertified pellets. *Renew. Energy* **2020**, *161*, 1059–1071. [CrossRef]
20. Madadian, E.; Akbarzadeh, A.H.; Lefsrud, M. Pelletized Composite Wood Fiber Mixed with Plastic as Advanced Solid Biofuels: Thermo-Chemical Analysis. *Waste Biomass Valorization* **2018**, *9*, 1629–1643. [CrossRef]
21. Commission Regulation (Eu) 2015/1189 of 28 April 2015 on the implementation of Directive 2009/125/EC of the European Parliament and of the Council as Regards the Ecodesign Requirements for Solid Fuel Boilers. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32015R1189&rid=1 (accessed on 3 September 2022).
22. Venturini, E.; Vassura, I.; Agostini, F.; Pizzi, A.; Toscano, G.; Passarini, F. Effect of fuel quality classes on the emissions of a residential wood pellet stove. *Fuel* **2018**, *211*, 269–277. [CrossRef]
23. Kleinhans, U.; Wieland, C.; Frandsen, F.J.; Spliethoff, H. Ash formation and deposition in coal and biomass fired combustion systems: Progress and challenges in the field of ash particle sticking and rebound behavior. *Prog. Energy Combust. Sci.* **2018**, *68*, 65–168. [CrossRef]
24. Vicente, E.D.; Vicente, A.M.; Evtyugina, M.; Carvalho, R.; Tarelho, L.A.C.; Paniagua, S.; Nunes, T.; Otero, M.; Calvo, L.F.; Alves, C. Emissions from residential pellet combustion of an invasive acacia species. *Renew. Energy* **2019**, *140*, 319–329. [CrossRef]
25. Quiñones-Reveles, M.A.; Ruiz-García, V.M.; Ramos-Vargas, S.; Vargas-Larreta, B.; Masera-Cerutti, O.; Ngangyo-Heya, M.; Carrillo-Parra, A. Assessment of Pellets from Three Forest Species: From Raw Material to End Use. *Forests* **2021**, *12*, 447. [CrossRef]