

Article

Impact of Ignition Technique on Pollutants Emission during the Combustion of Selected Solid Biofuels

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Abstract: Nowadays, heating using wood, briquettes, or pellets is a curious replacement to fossil fuels such as coal, oil, or gas. Unfortunately, the combustion of biofuels, especially in low-power boilers with unstable operating conditions, releases a lot of gas pollutants (e.g., carbon monoxide (CO), nitric oxide (NO), and various organic compounds) that are usually generated due to the incomplete product combustion. The combustion of biofuel in grate boilers with top-down ignition is a new approach, popular in society (mainly used for coal fuels), which improves the combustion process and reduces the amount of pollutants emitted. This study evaluated the impact of ignition techniques on the emission level of gas pollutants during the combustion of wood logs, briquettes, and pellets of pine in grate-based charging boilers. The combination of top ignition mode with pinewood logs allowed us to achieve a reduction of 6% in CO and sulfur dioxide (SO₂) emission into the atmosphere. However, the combination of top-down ignition mode with pellets and briquettes produced, in fully operational conditions, 1- to 18-fold higher levels of CO and SO₂ respectively, than bottom-up ignition, after an initial period of low level CO and SO₂ emissions. During the tests (mainly with ignition from top), substantial emissions of NO were observed of up to 400 mg·m⁻³ at 10% O₂. Therefore, further research is required to decrease emission related to the content of nitrogen in biomass. In this respect, research of impact on the combustion temperature of such emissions is needed.

Keywords: harmful gas; combustion; solid biofuels; top ignition combustion mode

1. Introduction

An important research topic in modern agriculture is reducing the environmental impact caused by the increasing consumption of energy [1] and primary material [2] in agriculture. Agricultural energy needs are primarily due to the energy consumptions of tractors, operational machines [3], water pumps, and cultivation in a controlled environment [4]. For this reason, nowadays in the agricultural sector smart control and sharing systems of renewable energy produced by sources such as photovoltaics [5], geothermal [6], solar thermal, and biomass are increasing.

However, there are many problems still to be addressed, such as the low energy transport capacity of the electrical net, which was not designed to transport the unstable energy produced from renewable sources, or the high costs of transporting solid fuel such as biomass, which requires a preliminary logistic study of harvesting and consumption points. A possible solution to these problems is represented by the idea of producing and consuming energy in small districts and therefore using integrated systems of renewable energy sources and energy vectors such as hydrogen [7] or biomass. In fact, one of the most used heating sources in the agricultural sector is biomass, and several studies have analyzed biomass both from the point of view of its quantification with modern

precision-farming techniques [8] and its environmental impact in terms of life cycle assessment and pollution. One way to reduce the displacement of biomass and improve its logistics is local re-use as digestate [9], composted material [10], or fuel for domestic heating. From this perspective, autonomous biomass home heating systems can represent an excellent solution. The disadvantages of these systems, however, are represented by their low efficiency and high emissions due to incomplete combustion.

Wood is still considered a particularly interesting fuel due to its common occurrence and energy properties (the calorific value and chemical composition of ashes), which allow obtaining a high thermal efficiency [11–13]. Heating using wood, briquettes, or pellets is an effective alternative to fossil fuels such as coal, oil, or gas. The advantages of these natural resources are the responsible treatment of the natural environment and their availability as raw materials of local origin. Furthermore, wood logs are one of the cheapest energy carriers that ensure low heating costs [14,15].

It is believed that combusting wood, like any herbaceous biomass, does not cause any harm to the environment in the context of CO₂ emissions; however, under certain conditions, biofuel combustion in individual heating systems can pose serious threats to the surroundings and society on a local scale [16,17]. When compared to coal, one unit of biofuel upon combustion releases high amounts of volatile gases and low amounts of energy [18]. In addition, the proportion of elemental carbon and organic carbon in the air leads to a transformation in the radiation balance of the earth and also changes the chemical (molecular) composition of clouds [19].

Combustion is a complex phenomenon which is mainly seen as physicochemical changes in the fuel caused by thermal decomposition occurring in a given phase and time [20]. The analysis of this process requires knowledge about the fuel properties and their impact on the course of combustion [21]. Some of the parameters that have the greatest impact on emissions include operation management [22,23], fuel characteristics [24], method of air supply [25], ignition technique [26], and the heterogeneous temperature distribution in the combustion chamber that generates so-called cold zones [27].

For biomass combustion, subsequent stages on the grate can be distinguished: drying, degassing, coke gasification, and slag cooling. To optimize oxygen supply, each of these processes should be considered individually [28,29]. The temperature in small-scale charging boilers is regulated in a different manner when compared to dust or fluidized boilers, in which case the temperature is controlled either by changing the fuel stream dispensed [30] or by changing the amount of oxygen supplied [31]. Contaminants generated during the combustion of biofuels, especially in low-power boilers and at untypical operating conditions (e.g., lower heat demand, which results in lower fuel consumption in the case of not very low outside temperatures) are usually incomplete combustion products which should be measured (controlled)—CO, nitric oxide (NO), organic compounds (polycyclic aromatic hydrocarbons, volatile organic compounds), and tarry parts or total suspended particles [32]. Furthermore, many operational parameters of the furnace, which are user-independent, affect the emission and thermal efficiency of the boiler. Gas emissions should be reduced as much as possible. Due to these reasons, secondary air is supplied to the chamber and combustion chamber insulation is provided. Despite these efforts, wood combustion increases the emission of unburned gas and particles, especially during ignition when the boiler and furnace are still cold. The method used for lighting up and maintaining the heating device during operation may contribute to the emission of gases [27].

Therefore, this study evaluated the impact of ignition technologies on pollutant emission during the combustion of wood logs, briquettes, and pellets of pine in grate boilers.

2. Materials and Methods

In this study, pine biofuel in the form of wood logs, briquettes, and pellets was used. Wood logs weighing approximately 100 kg were purchased from the fuel depot. The logs were divided into three parts: two parts (approximately 60 kg) were preshredded using a planner and the third part was used to prepare chips using a beater shredder with 10 mm diameter bore screens. The prepared material

was subjected to a compaction process in a flat die-pelleting device with a hole diameter of 6 mm and in a hydraulic briquetting machine with a briquetting sleeve of 50 mm internal diameter.

The selected physicochemical parameters were determined in the working condition for the biofuels:

- Geometrical features—diameter (D) and length (L) were directly measured with calipers, adapting for piece and briquette standard EN ISO 16127:2012 [33] for three replicates of randomly selected portions of fuel with a 100 + 1 g mass (pellets) or 10 briquettes and wood slivers;
- Moisture (MC)—calculated using the weight method according to the standard EN ISO 18134-3:2015 [34] for three replicates of each biofuel class;
- Volumetric density (VD)—calculated on the basis of geometrical features in randomly selected samples and weights of biofuel portions using the following formula:

$$VD = \frac{4 \cdot m}{\pi \cdot d^2 \cdot l'} \quad (1)$$

where VD —density of wood logs, briquettes, or pellets ($\text{kg} \cdot \text{m}^{-3}$); m —weight of a portion of fuel wood logs, briquettes, or pellets (kg); d —average diameter of briquettes or pellets/width of medium wood logs (m); and l' —sum of the length of wood slivers, briquettes, or pellets in the portion of fuel (m).

- Carbon (C), hydrogen (H), and sulfur (S)—measured by applying an automatic infrared analyzer according to the standard PN-G-04584:2001 [35] for three replicates from a sample taken of crushed pine biomass;
- Nitrogen (N)—measured with an automatic katharometer according to the standard CEN/TS 15104:2006 [36] for three replicates from a sample taken of crushed pine biomass;
- Lower heating value (LHV)—calculated after determining the combustion heat according to the standard EN ISO 18125:2017 [37] for three replicates from a sample taken of crushed pine biomass;
- Ash content (AC)—calculated according to the standard EN ISO 18122:2016 [38] for three replicates from a sample taken of crushed pine biomass.

Table 1 presents the physicochemical properties of the solid biofuels.

Table 1. Physical and chemical parameters of the solid biofuels used (in working condition).

Parameter (Average Values)	Unit	Pine Piece Wood	Briquettes Made of Pine Sawdust	Pellets Made of Pine Sawdust	
Length	L	m	0.250	0.039	0.047
Breadth/diameter	D	m	0.060	0.050	0.006
Moisture content	MC	%	10.00	9.69	9.78
Volumetric density	VD	$\text{kg} \cdot \text{m}^{-3}$	550	1027	965
Elemental composition	C	%		51.07	
	H	%		5.97	
	N	%		0.22	
	S	%		0.01	
Lower heating value	LHV	$\text{MJ} \cdot \text{kg}^{-1}$		17.46	
Ash content	AC	%		0.65	

To study the impact of the ignition technique on the emission of gas pollutants, testing stands were used which had a cuboidal combustion chamber surrounded by a water jacket closed with a bottom water grate (Figure 1). The combustion chamber had a capacity of 35 dm^3 ($0.26 \times 0.30 \times 0.45 \text{ m}$). The heat exchanger is a classic solution used in such boilers with two horizontal partitions with water channels. Ash from the hearth accumulated in a container under the grate and air was fed to the boiler under the grate by a fan. The water in the water jacket between the open type heat exchanger was circulated by means of a circulating pump. The water capacity of the water jacket was 30 dm^3 and the

storage tank capacity was 400 dm³. The test stand was constructed in such a way that made it possible to repeat the conditions prevailing during the combustion in typical low-power heating devices.

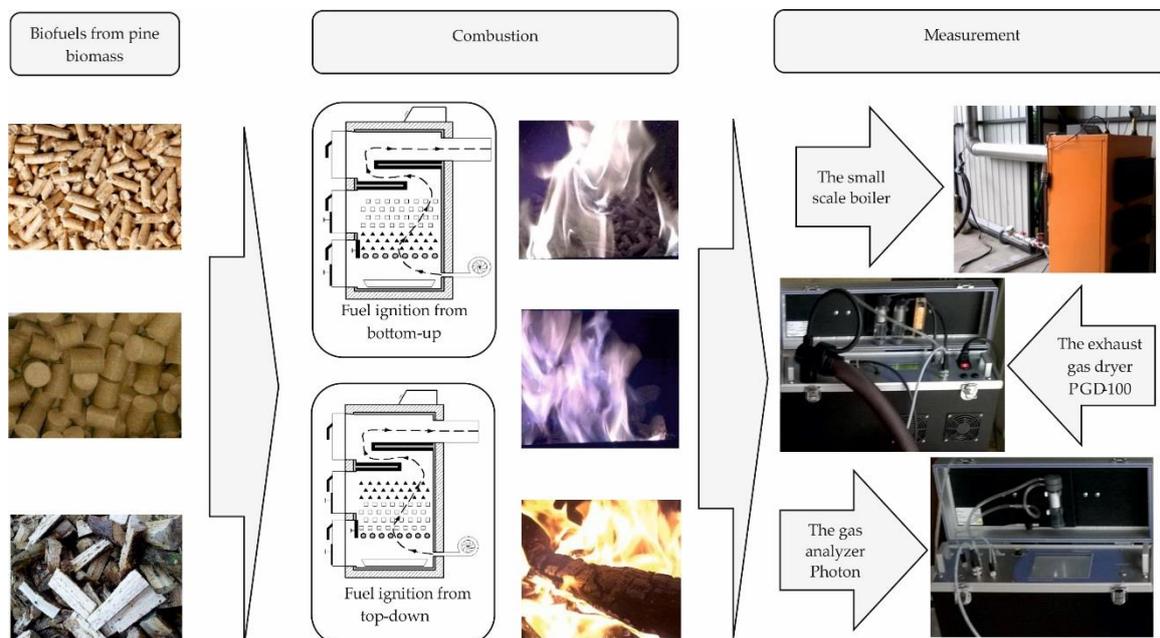


Figure 1. Scheme of stages of conducting an experiment (triangles mark the ignition initiation layer and squares indicate fuel).

During the tests, fuel portions (3 kg) were loaded into the boiler. The parameters of the combustion process were recorded immediately after setting the ignition initiator paper on fire, which consisted of five A4-sized sheets weighing 80 kg·m⁻² crushed into balls. The parameters of the exhaust gases were measured continuously—that is, from the initiation of ignition to the expiration of the reaction, for which the temperature of the exhaust gases was assumed to fall to 200 °C. This technique corresponded to obtaining a stabilized layer of heat forming a suitable base to initiate the flame during daily use while refueling. The results were saved to the analyzer's database every 4 s. The exhaust gases were collected from the chimney at a distance of 1 m from the boiler. The measuring probe was connected to the exhaust gas dryer PGD-100 (Madur Eljack Electronics). From this device, moisture-free gases with stable parameters went to the Photon flue gas analyzer (Madur Eljack Electronics). This device operates based on the nondispersive infrared sensors for the following gases: CO, CO₂, NO, and SO₂. The temperature was measured using a K-type thermocouple placed in the exhaust gas intake probe.

The recorded data were transferred from the analyzer to a PC and were used to calculate the excess air index and fuel demand. The air–fuel ratio (λ) was calculated using the formula [39]:

$$\lambda = 20.95/(20.95 - O_2), \quad (2)$$

where O₂—oxygen content by volume in dry gas (%).

The demand for fuel in the combustion process was calculated as the quotient of the weight of the sample combusted to the time of combustion and expressed in kg·h⁻¹.

Next, data from the completed combustion processes were used to calculate the loss of exhaust gases (q_A), which was defined as the temperature difference of the exhaust gases and the temperature of the mixture being combusted in relation to the fuel properties and the amount of oxygen in the exhaust gas. The following formula was used to calculate q_A [39]:

$$q_A = (t_A - t_L) \cdot \left(\frac{A_2}{20.95 - O_2} + B \right), \quad (3)$$

where q_A —loss of exhaust gases (%); t_A —gas temperature ($^{\circ}\text{C}$); t_L —temperature of the combusted mixture ($^{\circ}\text{C}$); O_2 —volume of oxygen in dry gas (%); A_2 —coefficient characteristic of fuel (for biomass, it is 0.650); and B —coefficient characteristic of the fuel (for biomass, it is 0.008).

The concentration of CO, NO, and SO₂ in the exhaust gases was referred to the volume of dry exhaust gas with 10% oxygen content under normal conditions ($\text{mg}\cdot\text{m}^{-3}$) of 0 $^{\circ}\text{C}$ and 1013 mbar, according to the guidelines contained in the standard PN-EN 303–5:2002 [40].

The results obtained were divided into phases lasting 600 s and analyzed statistically. The consistency of the results with the normal distribution was verified using the Shapiro–Wilk test, and the uniformity of variance was estimated by applying the Brown–Forsyth test. When there was a lack of variance homogeneity, the Kruskal–Wallis test was used. However, the Spearman rank correlation test was used to describe the relationship between individual variables due to the lack of normal distribution for this data. The observed differences were considered statistically significant at the significance level of $p < 0.05$.

3. Results

Table 2 presents the average values (from three replicates) of physical parameters describing the course of the tests of combustion.

Table 2. Physical parameters of the combustion process.

Ignition System	Shape of Fuels	Air Flow ($\text{m}\cdot\text{s}^{-1}$)	Fuel Consumption ($\text{kg}\cdot\text{h}^{-1}$)	Air Excess Coefficient (-)	Exhaust Gas Temperature ($^{\circ}\text{C}$)	Loss of Exhaust Gases (%)
Bottom-up	Logs	1	4.16	3.41	253	24
	Briquette	1	4.89	5.11	292	24
	Pellets	1	4.89	2.40	344	23
Top-down	Logs	1	4.17	3.26	301	29
	Briquette	1	4.15	2.41	363	25
	Pellets	1	4.03	3.60	381	31

All the tests were carried out using the fuels selected for testing the air flow supplied from the bottom to the grate at an air flow of $1 \text{ m}\cdot\text{s}^{-1}$. During the tests, the fuel consumption was between 4 and $5 \text{ kg}\cdot\text{h}^{-1}$. It was noted that in most of the tests conducted, the demand for fuel decreased for the top-mode ignition technique; only for wood were the values similar. These trends were also marked for the value of the excess air coefficient. In the wood group, the excess air was very similar and was just over 3. On the other hand, for the other biofuels it was observed that briquettes with the bottom-up ignition system were combusted with an excess air of about 5, while with the top-fire one, the combustion proceeded with excess air at the level of 2.5. During the combustion of pellets, the relations were reversed: for the top-down technique, combustion was realized with an excess air of 3.6, and for the traditional technique it was 2.4. The exhausting gas temperature in the bottom-up technique ranged from $253 \text{ }^{\circ}\text{C}$ (wood) to $344 \text{ }^{\circ}\text{C}$ (pellets), while for the top-down technique the flue gas temperatures were around $30\text{--}50 \text{ }^{\circ}\text{C}$ higher. This resulted in a 5–6% higher loss of exhausting gases for the top-down ignition as compared to the bottom-up technique (Table 2).

The indicators of CO emission from the combustion of the selected biomass forms are shown in Figures 2 and 3.

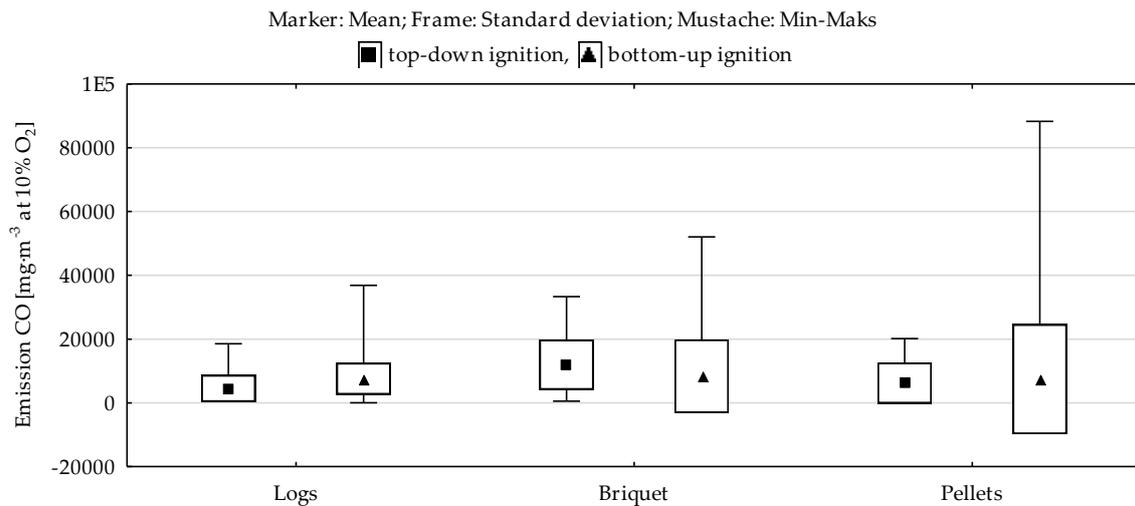


Figure 2. Indicators of carbon monoxide emission during the combustion of the selected biomass forms.

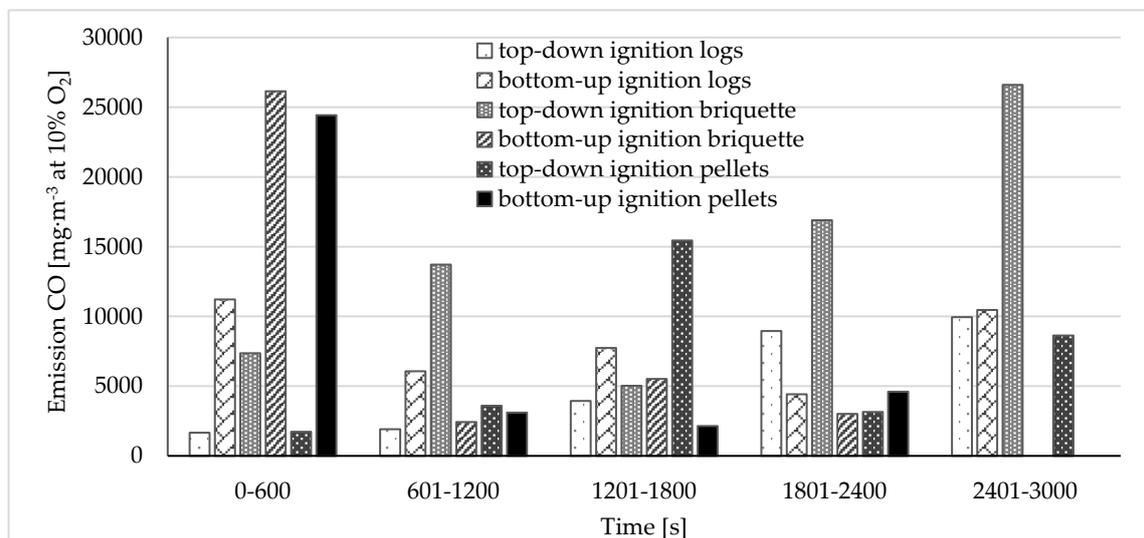


Figure 3. Changes in carbon monoxide emission during the combustion of the selected biomass forms (average values for separate combustion phases and ignition techniques).

When combusting the wood logs, briquettes, and pellets with the fuel system ignited from the top, usually a slightly lower average CO emission was observed than in the case of bottom-up combustion. For briquettes only, no benefits of the ignition technique from above were observed. However, for all other forms of biofuels, the top ignition resulted in lower maximum emissions (Figure 2). In the aspect of separated combustion phases, the obtained values of CO emission indicators converted into a 10% O₂ reference state in the exhaust gases were much smaller in the case of the top ignition system in the separated first and second combustion phases. In the subsequent phases, the effect of top ignition was not so favorable.

During the combustion of briquettes, large variations in gas emissions occurred, during which the placement of the initiating layer at the top of the bed led to the rapid penetration of burning or glowing fractions from the surface layer into the deposit downward between fairly wide spaces and individual fuel logs. This caused a very fast and deep ignition of the bed, which resulted in increased combustion and thus a high CO emission. During the third phase of pellet combustion, the remaining part of the fuel was subject to rapid ignition, leading to an increased CO emission. The lowest CO emission in the top-down ignition technique was observed during the combustion of the wood logs (Figure 3). A statistical analysis of the results showed significant differences between the two combustion systems

for wood logs and briquettes ($p = 0.000$ and 0.000 , respectively). However, in the case of pellets, there were no significant differences observed between the two combustion systems ($p = 0.743$).

Figures 4 and 5 present the factors for SO_2 emission from the combustion of the selected biomass forms.

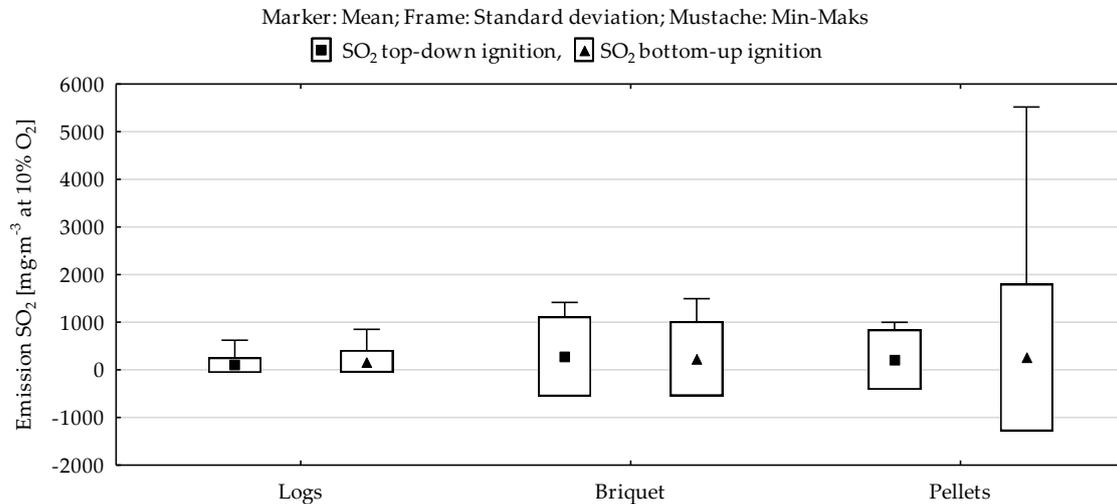


Figure 4. Indicators of sulfur dioxide emission during the combustion of the selected biomass forms.

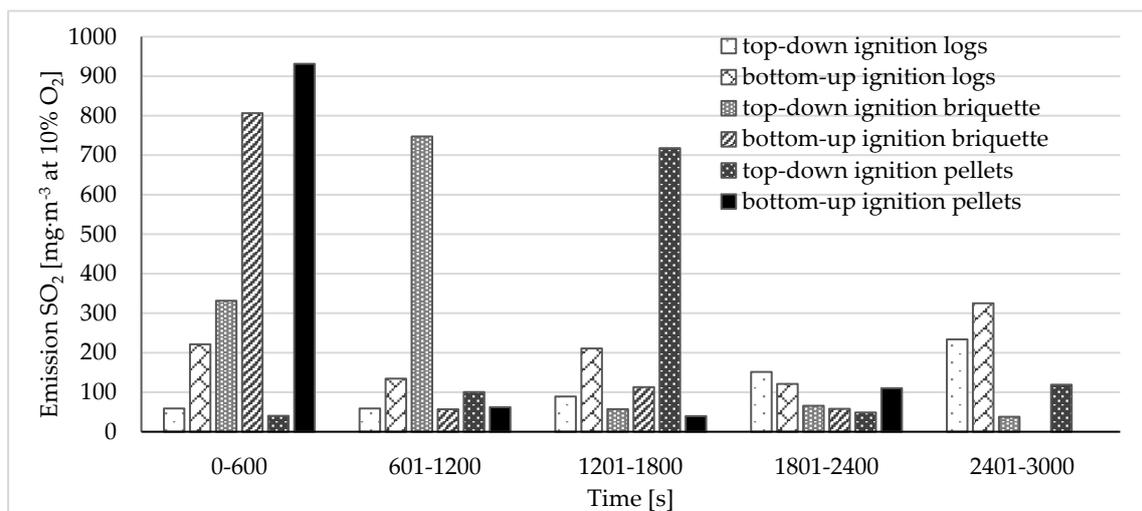


Figure 5. Changes in sulfur dioxide emission during the combustion of the selected biomass forms (average values for separate combustion phases and ignition techniques).

According to our results, regardless of the ignition system applied the average levels of SO_2 emission were slightly different for all three biofuels. When the bottom-up system was used for the wood logs and briquettes, slightly higher maximum emission values were obtained, whereas the same system produced much larger values for pellets (Figure 4). During the first and second stages of combustion, a higher variation and a smaller emission of SO_2 were recorded for the top-down ignition system compared to the bottom-up system. In subsequent phases, the top-down ignition system did not have any effect on emissions. A large variation was recorded in CO levels during the combustion of the briquettes and pellets (Figure 5). The statistical analysis showed significant differences between the two combustion systems for the wood logs and briquettes ($p = 0.000$ and 0.000 , respectively), whereas for the pellets no significant differences were noted between the two combustion systems ($p = 0.827$). Figures 6 and 7 present the indicators of NO emissions for the two combustion systems.

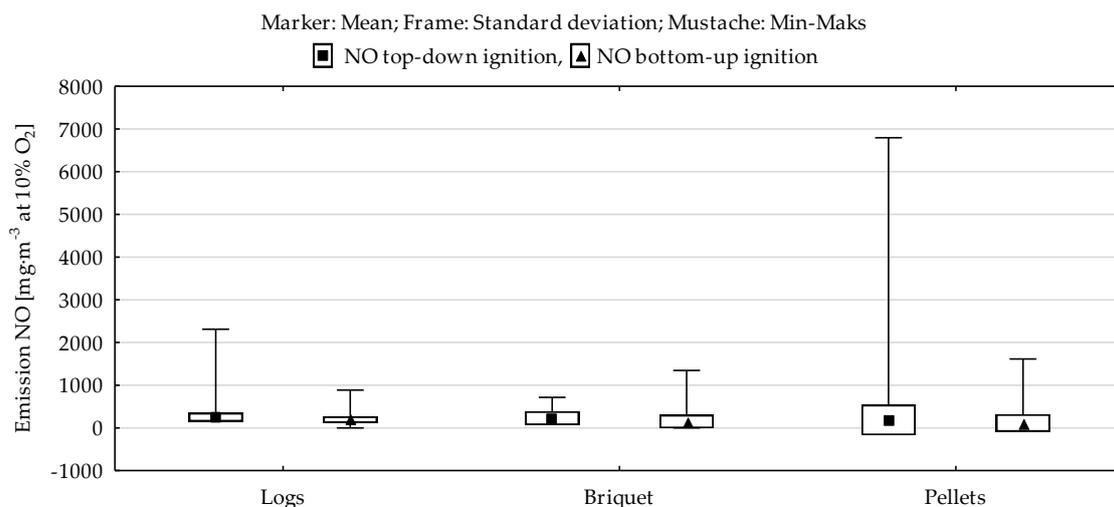


Figure 6. Indicators of nitric oxide emission during the combustion of the selected biomass forms.

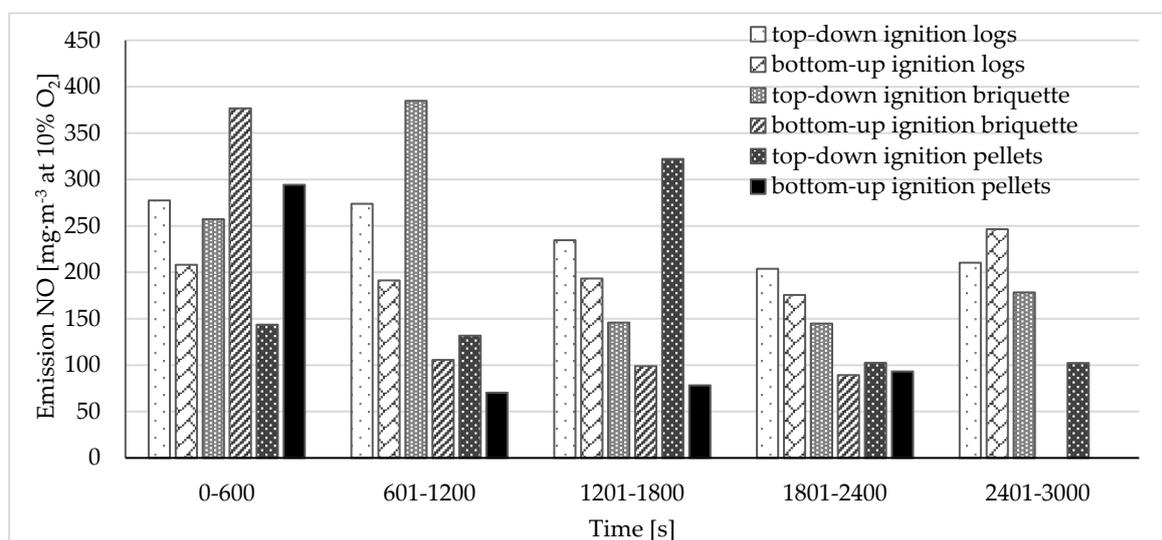


Figure 7. Changes in nitric oxide emission during the combustion of the selected biomass forms (average values for separate combustion phases and ignition techniques).

According to our results, regardless of the ignition system applied the average levels of NO emission were very similar. The top-down ignition system yielded higher maximum emission values for the wood logs and pellets (Figure 6). During the separated second, third, and fourth combustion phases, a greater variation and higher emission of NO were recorded for the top-down ignition system compared to the bottom-up system. Large variations were observed in NO emission during the combustion of the briquettes and pellets (Figure 7). The statistical analysis showed significant differences between the two combustion systems for all three biofuels ($p = 0.000, 0.000, \text{ and } 0.000$, respectively).

Table 3 presents the results of the nonparametric Spearman rank correlation test. This test showed significant differences between the values obtained for the individual forms of biofuels, as well as between the two ignition systems. For two combustion systems and used fuels, the strongest positive correlations show the dependence of CO and SO₂. While the correlation of NO emission with CO emission was usually positive, there was a strong negative correlation when combusting the wood with the top-down ignition system. During combustion with top-down ignition, the NO emission showed a weak positive dependence on the temperature of the exhaust gases, whereas with bottom-up ignition these relationships were not so repeatable, indicating a lack of significance in the group of

wood and briquettes. Additionally, there were positive correlations between SO₂ and NO that were even quite strong in the bottom-up combustion group. However, for the wood logs these values were different from others. It was also interesting that the top-down ignition had strong negative correlations between the oxygen content in the exhaust, while these relationships during combustion with a bottom-up ignition had little importance for the briquettes and pellets (Table 3).

Table 3. Spearman correlation coefficient R for the relationship between the gas combustion products (values recorded in bold are statistically insignificant).

Variables	Combustion Ignition	Logs	Briquette	Pellets
CO (mg·m ⁻³ at 10% O ₂) vs. SO ₂ (mg·m ⁻³ at 10% O ₂)	Top-down	0.927	0.409	0.979
	Bottom-up	0.885	0.932	0.964
CO (mg·m ⁻³ at 10% O ₂) vs. NO (mg·m ⁻³ at 10% O ₂)	Top-down	-0.751	0.359	0.398
	Bottom-up	0.035	0.697	0.590
CO (mg·m ⁻³ at 10% O ₂) vs. T _{gas} (°C)	Top-down	-0.402	-0.425	0.279
	Bottom-up	-0.525	-0.030	0.342
CO (mg·m ⁻³ at 10% O ₂) vs. O ₂ (%)	Top-down	0.126	0.324	-0.375
	Bottom-up	0.478	0.710	0.381
SO ₂ (mg·m ⁻³ at 10% O ₂) vs. NO (mg·m ⁻³ at 10% O ₂)	Top-down	-0.582	0.406	0.453
	Bottom-up	0.194	0.768	0.651
SO ₂ (mg·m ⁻³ at 10% O ₂) vs. T _{gas} (°C)	Top-down	-0.526	0.342	0.225
	Bottom-up	-0.595	-0.094	0.342
SO ₂ (mg·m ⁻³ at 10% O ₂) vs. O ₂ (%)	Top-down	0.363	-0.439	-0.316
	Bottom-up	0.598	0.782	0.408
NO (mg·m ⁻³ at 10% O ₂) vs. T _{gas} (°C)	Top-down	0.343	0.323	0.218
	Bottom-up	0.044	-0.005	0.329
NO (mg·m ⁻³ at 10% O ₂) vs. O ₂ (%)	Top-down	0.068	-0.402	-0.246
	Bottom-up	0.134	0.805	0.580
T _{gas} (°C) vs. O ₂ (%)	Top-down	-0.830	-0.960	-0.971
	Bottom-up	-0.848	-0.188	-0.032

4. Discussion

The differentiation of results obtained in the combustion process of various forms of solid biofuels seems to be related to the movement of the combustion front and deposit penetration caused by the variation in fuel granulation and, thus, different spaces between grains in their volume. These spaces, when combusting with a top-down ignition, not only determine the flow of air mixed with pyrolytic gases through the bed but also facilitate the penetration of burning fuel parts deep into the bed due to gravity. This accelerates the combustion process, thereby reducing the effect of the located postcombustion layer on top of the bed. Using ignition in the top of the portion's fuel reduces the CO emission in the initial combustion phase. However, this emission rapidly gains strength due to the fuel being absorbed by the flames. In the subsequent stages of combustion, a high temperature zone is lost, which reduced the formed carbon oxides. However, during combustion with bottom-up ignition, the co-current flow of gases through the free spaces between fuel particles causes the intensive evaporation of volatile parts, which ceases to be relevant in subsequent combustion phases. Other researchers point to such relationships related to fuel particle sizes. Ryu et al. [41] compared the combustion rate and weight loss during the ignition period for different sizes of pine wood particles. In the initial phase, small particles are characterized by a higher combustion rate. The loss of mass during the period of ignition spread suggests that the amount of coke residue also decreases for smaller particles. In the case of 35 mm particles, the speed of the ignition front is, however, greater compared to 20 mm particles, whereas the loss of mass and combustion rate are lower. This is explained by the better contact of fuel with hot gases due to larger empty spaces in the deposit. Additionally, Ryu et al. [41] showed that in a fixed combustion bed of biomass samples with different properties, two samples from woody raw materials had a faster ignition propagation than that of the pellet samples. Furthermore, the rate of ignition propagation was inversely proportional to the bulk density, and the combustion rate decreased

linearly, which was proportional to the change in bulk density, the differences between samples being relatively small. Furthermore, Kaer [42,43] and Van der Lans et al. [44] indicated two models of the combustion process. The first mode was characterized by degassing the fuel from the front, which moved down and then up, oxidizing the coke residue. In the second mode, the fuel degassing and oxidation of the coke residue were initiated on the grate and moved up. The ignition speed was much faster in the second mode of operation and the gas temperature was lower. Thunman and Leckner [45] and Thunman et al. [46] also supported the existence of two combustion modes.

Bradelet et al. [26] studied the effects of CO emission from a top-firing fuel, during which the pyrolytic gases were combusted in the heat layer formed on top of the deposit. They reported a reduction in the levels of CO emissions in addition to other hydrocarbons. However, the total emissions they found did not apply to the combustion phases and the form of biofuel used.

In this study, the SO₂ emissions were higher in the case of combustion with the bottom-up ignition system. Bradelet et al. [47] hypothesized that the sulfur gas migrates in the suspended particles, where it is oxidized to produce SO₂. This study showed that SO₂ emission is strongly associated with CO emission, indicating the displacement of unburnt deposit parts.

This study also revealed variation in NO emission. During combustion with a bottom-up ignition, the NO emission was lower than that of combustion with a top-down ignition, which may be due to changes in the average temperature of the exhaust gas. The temperature during combustion with the top-down ignition was about 30–50 °C higher than that of the bottom-up combustion system. Vicente et al. [47] found a similar, though less significant, change in temperatures between the two modes of ignition.

Research aiming to improve the efficiency of combustion systems and reduce emissions dust, CO, and NO_x from low-power heating devices is part of legislative activities [48]. Kubica [31] and Reichert et al. [49] have indicated the need to change the combustion technology in low-power heating devices. The top-down model of ignition is a much faster way to improve combustion, especially when using wood logs. However, top-down ignition does not bring benefits over the entire period of combustion. A communication campaign can change the heating habits of users and can significantly reduce carbon monoxide emission from the household fuel furnace.

5. Conclusions

The use of various forms of biofuels in the grate boiler, as well as change in the ignition mode, significantly affects gas emission. This is due to the size of the particles and the penetration of flames through the free spaces between parts of the fuel. The application of top-down ignition mode along with the use of wood logs helps to significantly reduce the emission of harmful gases such as CO and SO₂ into the atmosphere. This study showed that the combustion of pellets and briquettes in a top-down ignition system produced low CO and SO₂ emissions during the initial stages, where at the same moment the bottom-up combustion system produced more emissions. However, the division into combustion phases showed that the CO and SO₂ levels were 1- to 18-fold higher with ignition from the bottom after an initial period of low-level emissions of these compounds. It is believed that this ignition system can work when the CO post-combustion layer is maintained for a long time in the combustion chamber in the top of fuel portion. However, it is doubtful that small combustion chambers will meet such requirements. In addition, when using biofuels, NO emission should be particularly controlled when the combustion temperature increases. The diversity in gas emissions during the combustion of molded fuels, briquettes, and pellets indicates the need for the adjustment of combustion techniques in the context of combustion phases. Therefore, further research is warranted to improve the combustion process of solid biofuels in low-power heating devices with a small combustion chamber, especially those that are refilled periodically.

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Writing–review & editing, A.K., A.P. and A.S.A. All authors have read and agreed to the published version of the manuscript.

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