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Emission of Harmful Substances from the Combustion of Wood Pellets in a Low-Temperature Burner with Air Gradation: Research and Analysis of a Technical Problem

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Abstract: This paper includes a discussion of the results of tests concerning changes in the thermal and emission parameters of a boiler fuelled with wood biomass under the influence of air gradation in the combustion process. The test results ensure insight into the combustion process of wood biomass with air gradation, which significantly affected the operation of the device, increasing the mass concentration of the emitted nitrogen oxide (NO_x) by combustion temperature lowering, especially in the afterburning zone. The authors observed an increase in the emission of particulate matter (PM) and carbon monoxide (CO) related to the change in the combustion process stoichiometry. The tests were carried out with the use of a heating boiler equipped with an automatic pellet burner. Apart from the mass concentration measurement of the pollution emitted, the tests focused on the measurements of temperature and oxygen levels in the flue gas. The objective of the tests was to confirm the applicability of the air gradation techniques in biomass combustion in order to reduce the emission of harmful substances from heating boilers, which is a technique that has recently been used in this group of devices. The test results obtained confirm the necessity for reorganising the technical systems of the currently used pellet burners and implementing further empirical tests.

Keywords: boilers; furnaces; burners; wood pellet; emission

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Citation: Ciupek, B.; Nadolny, Z. Emission of Harmful Substances from the Combustion of Wood Pellets in a Low-Temperature Burner with Air Gradation: Research and Analysis of a Technical Problem. *Energies* **2024**, *17*, 3087. https://doi.org/10.3390/en17133087

Academic Editors: Yonmo Sung and Cheol-Hong Hwang

Received: 18 April 2024
Revised: 31 May 2024
Accepted: 20 June 2024
Published: 22 June 2024

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1. Introduction

Harmful substances (gas and solid) generated in the wood pellet combustion process, released by the emitter (flue gas duct, stack, flue gas pipe), firstly pollute the atmospheric air and then surface waters and soil [1]. Harmful combustion products spreading in the atmosphere may undergo secondary chemical transformations resulting from the impact of solar electromagnetic radiation or the presence of oxygen radicals and particulate matter [2]. In the final phase, a portion of pollutants remain in the air and another portion settles down on the earth. This effect results in the pollution of the air zone and the ground zone of the environment in which people live [3].

Decreasing the emission of harmful substances, such as carbon monoxide (CO) or nitrogen oxides (NO_x), during fuel combustion falls within the primary methods of their reduction [4]. These methods consist of direct interference with the combustion process when it takes place in the combustion chamber [5]. The most common [6] primary methods of reducing harmful gaseous substances emitted during combustion are as follows:

- Combustion gradation [7];
- Feeding of ammonia or carbamide solution [8];
- Air temperature reduction [9].

Combustion gradation consists of the division of a typical combustion process into stages at which combustion takes place with air deficiency or excess (varied excess air

ratio—λ) or a variable equivalence ratio (Φ). Currently, burners or furnaces installed in boilers or combustion chambers of low-temperature heating boilers generally employ the following two combustion gradation technologies:

- Air gradation;
- Fuel and air gradation.

In the event of combustion with air gradation, in the first stage, an oxidant is supplied in an amount that ensures the original ratio of air excess in the following range: $\lambda \geq 0.6–0.8$. Combustion in this phase is sub-stoichiometric, and in such conditions, there is a high concentration of reducing radicals (HCN, CH_i, and NH_i) that reduce NO_x generated in the combustion process. Nevertheless, the drawback of this solution is the danger of forming a considerably high quantity of incomplete or partial combustion products, especially carbon monoxide (CO) and carbon black (defined as PM—particulate matter). In addition, in the event of biomass combustion in the form of wood pellets, there is a significant concentration of carbon (C) in ash and slag deposited in the combustion chamber and a part of the boiler heat exchanger right after the first flue gas return. This problem is often solved by the second combustion stage, in which carbon monoxide, carbon black, and carbon are afterburned by secondary air fed to the afterburning zone in an amount guaranteeing the combustion process for this zone, which is defined by an excess air ratio of $\lambda \geq 1.0$. An idea of the air gradation process is presented in Figure 1.

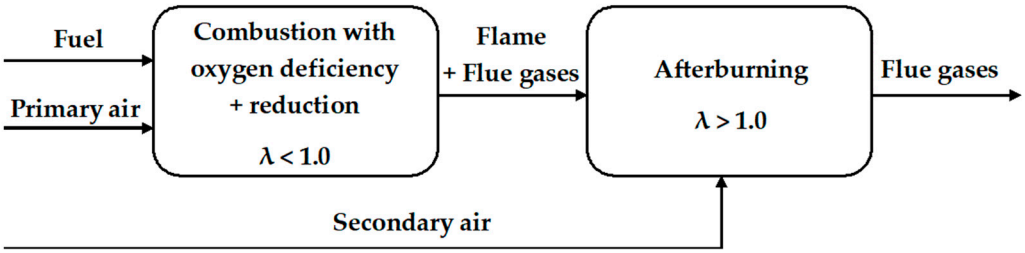

Figure 1. Diagram of combustion process for air gradation.

In the event of combustion with fuel and air gradation in the first stage, regular combustion is performed, with the air excess (λ) corresponding to the type of fuel that is combusted. In this stage, a normal quantity of nitrogen oxide (NO_x) is emitted. In the subsequent stage, additional fuel is fed to create a reduction zone with the following air excess ratio: $\lambda \geq 0.6–0.8$. Such conditions enable the generation of reductive compounds and radicals that convert NO to N_2, reducing the concentration of NO_x in flue gases. In the final stage, additional air is fed to obtain the following total ratio of air excess: $\lambda \geq 1.0$, which is to afterburn CO, carbon black, and carbon, which together with ash and slag, is taken to the ash pit and the exchange part of the boiler. An idea of the fuel and air gradation process is presented in Figure 2.

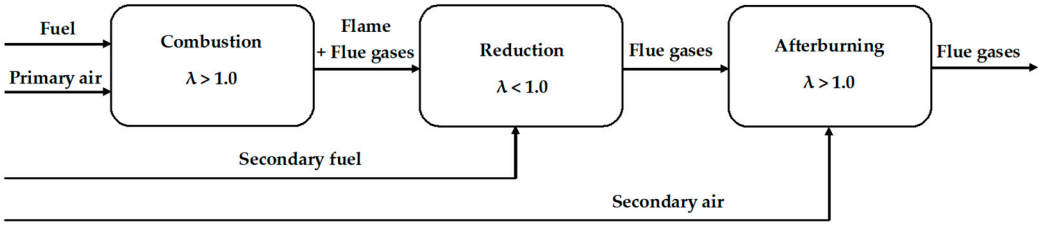

Figure 2. Diagram of combustion process for fuel and air gradation.

When analysing both combustion gradation methods, a significant role is played by the following:

- The level of air excess ratios (λ) for a given combustion stage;
- Temperature (T) in respective combustion zones;

- Time (τ) of flue gases staying in a respective reduction and combustion zone;
- Volume of the emission of a given harmful flue gas component [10,11].

The pressure of the inlet air to the burner or individual sections of the air distribution into primary and secondary burner air or of the inlet air behind the burner can have a strong influence on the combustion process and, consequently, the emission of harmful substances. The spray cooling process can be used to lower the temperature of the flue gas in order to reduce the emissions of components strongly related to the combustion process temperature and the resulting combustion phases (CO and thermal NO_x). Spray cooling is characterised by a high heat transfer coefficient and the maintenance of a low cooling surface temperature, which directly affects thermal processes that have a strong effect on the level of pollutants emitted (e.g., in radical processes) [12].

The literature analysis [13,14] indicates that the equilibrium sum of nitrogen compounds marked as NO_x referred to the air excess ratio in the following range: $\lambda = 0.7–0.9$; the minimum concentration of the nitrogen compound sum is significantly higher than the equilibrium emission. In the event of temperature for poor mixtures ($\lambda > 1$) the temperature increase clearly enhances the increase in NO_x concentration in flue gases. Whereas, for rich mixtures ($\lambda < 1$), the temperature increase influences the reductive compound concentration, affecting the total reduction of emitted NO_x. In the event of $\lambda < 0.9$, mainly in flue gases, the dominant compounds are HCN and NH_3; whereas, when $\lambda > 0.9$, the main compounds are NO and NO_2. If the temperature increases above 1200 K, the equilibrium share of NO is higher than that of NO_2, which is related to the minimum value of free enthalpy for the considered thermodynamic system.

The combustion gradation rules are usually well-known and described in the literature [15–19]. Nevertheless, the course mechanisms of respective phenomena and their physical–chemical descriptions, as well as their practical uses in technology, require further research, which is conducted all the time in various research centres.

2. Materials and Methods

The tests were divided into two stages, in which the operation configuration of the pellet burner, equipped with a movable grate, with a rated power of 25 kW, installed in the heating boiler, BIOVERT 21 (Pleszew, Poland), was changed. The tests were carried out for 100% of the burner power (25 kW), with a deviation of ±2 kW resulting from thermal loss generated by the test stand and released to the environment. Conventionally, the burner installed in the boiler conducts a combustion process with the gradation of air needed for combustion; nevertheless, for these tests, its structure was also adapted to the performance of such a combustion process. A technical change on the side of the air supply channels allowed us to perform the combustion process with air gradation, in which the excess air ratio for the pre-combustion zone was approximately $\lambda = 0.85$. This value results from the number and geometry of air supply channels (oval openings, 45 pcs., diameter of 0.05 m) responsible for supplying air to the pre-combustion zone of the burner. A total of 81 pcs. of such openings are present in the afterburning space (zone of supplying secondary air). When testing the process, combustion was performed for both burner configurations (with air gradation and without air gradation) for the final excess air ratio (λ) and the full operation cycle, with a range of $\lambda = 1.00–2.40$, adjusting accordingly the air stream supplied by the burner air supply system.

Measurement data were recorded on a test bench equipped with a National Instruments measurement system. The system collected data from the flue gas analysers, and the measurement system (LabVIEW 2019) recorded the temperature in the chimney with a resolution of 5 s. The flue gas temperature was the average of the measurements taken using five type K thermoelectric sensors (NiCr-Ni) mounted in the chimney. The fuel consumption of the boiler was determined by measuring the weight of the biomass load before and after the tests. Based on the amount of fuel burned during the tests, the boiler output was determined. The mass concentrations of carbon monoxide (CO), nitrogen oxides (NO_x), and particulate matter (PM) were converted to mg/m^3 for 10% O_2 in the flue

gas, according to the measurement method for low-temperature boilers described in the standard [20].

2.1. Heating Devices

The test object was a biomass boiler (BIOVERT 21, with automatic fuel feed) with a nominal power of 21 kW manufactured by Walendowscy, Pleszew, Poland (Figure 3). The boiler was fuelled with biomass pellets with a minimum grain diameter of 5 mm and an average length of 15 mm (ranging from 5 mm to 25 mm), operating at an output of approximately 25.0 kW. The boiler met the requirements of class five according to EN 303-5:2012 [20]. The operation of the boiler was controlled by a microprocessor controller. For operation at nominal power (25 kW), the recorded fuel consumption was about 3.03 $kg \cdot h^{-1}$, and the intake air demand was about 22.55 $m^3 \cdot h^{-1}$. Figure 2 shows the test facility [21].

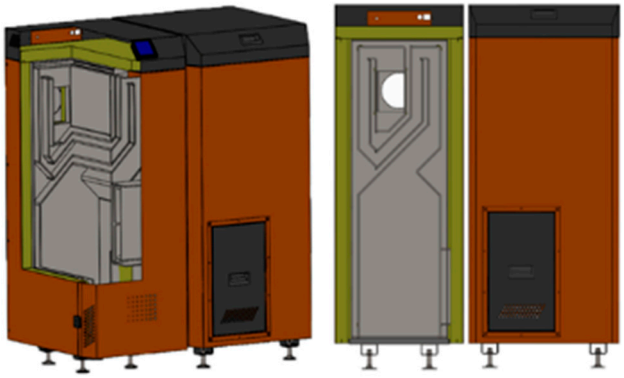

Figure 3. BIOVER 21 boiler used in the tests.

2.2. Pellet Burner

The tests were carried out with the use of a pellet burner (ECOMAT 25 model) designed for the combustion of wood biomass pellets, which was made by Termotechnika, Góra Puławska, Poland (Figure 4). The declared range of the burner power is 5.6–25.0 kW, the declared thermal efficiency is 98%, the average electric power consumption is 40 W/h, and the feeder maximum efficiency is 8.5 kg/h (allows to obtain approx. 38 kW of thermal power). The burner structure is patent protected (PL 222330) within the carbon black afterburning system and the use of the flue gas catalyst. In addition, the burner is equipped with an inertial return flap, which prevents flame from going back to the pellet chute shaft from the feeder, an electronic furnace control by means of a photocell, burner power modulation in the range of 10–100% of the rated power, multi-point supply of primary and secondary air in the burner combustion chamber, and automatic ash removal from the furnace owing to the movable grate activated cyclically by means of an external actuator [22]. The gradation of combustion air is carried out by the distribution of combustion air divided into a primary combustion zone and a post-combustion zone located away from it and the burning fuel bed, which is realised by secondary air ducts. In the standard configuration, the burner for the combustion process uses only the primary zone of air supply located in front of the burnt fuel bed. For this configuration, the burner operates in the following range of excess air ratio: λ = 1.00–2.40. For the purpose of this research, an additional part was installed behind the zone of the burnt bed, which is responsible for supplying secondary air to the zone outside the bed of burnt fuel, but in the zone of functioning in the burner flame and hot combustion gases. For the configuration with an additional secondary air supply zone, the burner operation was also within the range of the following excess air ratio: λ = 1.00–2.40. Therefore, the combustion air staging system for the design of a low-power pellet burner (less than 50 kW) in the configuration submitted for testing is associated with the following two zones of combustion air supply: the primary zone (in the classic configuration mainly responsible for supplying combustion air) and the secondary zone (responsible for supplying air for post-combustion of residues generated by the primary

zone). These configurations make it possible to verify whether a disadvantage associated only with the gradation of post-air for the biomass pellet combustion process will adversely affect the post-emergence of harmful substances associated with incomplete combustion.

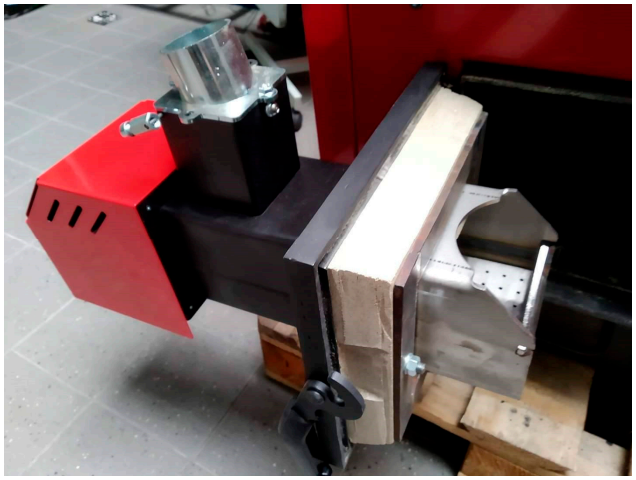

Figure 4. ECOMAT 25 burner used in the tests.

2.3. Chemical Parameters of the Fuel

The biomass used in the tests (pinewood pellets) was subjected to a technical analysis according to the standard [23–27]. The results of the analysis of biomass types and their higher caloric value (Q_s) and lower calorific value (Q_i) are presented in Table 1.

Table 1. Analysis of the biomass used during the research.

Type of Measurement	Pinewood Pellets
Hygroscopic moisture content (W_h) %	1.93
Excess moisture content (W_{ex}) %	3.14
Total moisture content (W_t) %	5.00
Volatile matter %	73.61
Ash content %	0.47
C %	54.74
S %	0.09
H_2 %	4.97
N_2 %	0.19
O_2 %	34.54
High calorific value (Q_s) MJ/kg	14.93
Low calorific value (Q_i) MJ/kg	14.32

2.4. Emission Measurement Devices

The tests were performed using exhaust gas analysers equipped with electrochemical measurement cells. The first instrument was a Testo 350-S analyser (Testo SE & Co. kGaA, Titisee-Neustadt, Germany) in a two-component configuration (controller and analyser). The analyser was equipped with an O_2 measurement cell with a volume measurement range of 0–25% and a measurement error of ±0.8% and was fitted with an NO sensor with a measurement range of 0–3000 ppm and a measurement error of ±1.5 ppm.

The second instrument used in the tests was a Testo 380 particle analyser (Testo SE & Co. kGaA, Titisee-Neustadt, Germany) coupled with a Testo 330-2 LL exhaust gas analyser (Testo SE & Co. kGaA, Titisee-Neustadt, Germany). The Testo 380 was used to measure particulate matter in the range 0–300 mg/m^3 and carbon monoxide (CO) concentration (0–8000 ppm), with a measurement error of ±10 ppm for the measurement point (0–200 ppm) and ±20 ppm for the measurement point (201–2000 ppm), as well as

nitrogen oxide (NO_x) concentration (0–3000 ppm), with a measurement error of ± 5 mg/m^3 (0–100 ppm) [28]. Figure 5 presents the aforementioned measurement devices.



Figure 5. Flue gas analysers used in the tests. **Left**: Testo 350 S; **right**: Testo 330-2 LL with Testo 380.

2.5. Formulas Used for Calculations

The following equations and mathematical formulas based on the fundamentals of the stoichiometry of combustion processes and the resultant thermodynamic parameters of the conventional heat sources used were applied to develop the test results.

The conversion of the CO content in flue gases from the value measured in ppm into mg/m^3 for 10% O_2 in flue gases was carried out with the use of the following equation:

$$\mathrm{CO}\left[\mathrm{mg/m^3}\right] = \mathrm{CO[ppm]} \cdot 1.250 \cdot \frac{20.95\% - 10\%}{20.95\% - \mathrm{O_2[\%]}} \quad (1)$$

The conversion of the NO_x content in flue gases from the value measured in ppm into mg/m^3 for 10% O_2 in flue gases was carried out with the use of the following equation:

$$\mathrm{NO_x}\left[\mathrm{mg/m^3}\right] = \mathrm{NO[ppm]} \cdot 2.056 \cdot \frac{20.95\% - 10\%}{20.95\% - \mathrm{O_2[\%]}} \quad (2)$$

This conversion takes place from the NO content in flue gases into NO_2, representing the total emitted nitrogen oxide (NO_x) due to the oxygenation of nitrogen oxide II to nitrogen oxide IV in higher atmosphere layers.

The carbon dioxide content (CO_2) for biomass combustion is calculated with the use of equation [29] and with the use of the $CO_{2,max}$ value, which is 19.4% for the wood biomass, as follows:

$$\mathrm{CO_2[\%]} = 19.4 \cdot \left(1 - \frac{\mathrm{O_2[\%]}}{20.95\%}\right) \quad (3)$$

The excess air ratio (λ) is calculated using the following equation:

$$\lambda = \frac{20.95\%}{20.95\% - \mathrm{O_2[\%]}} \quad (4)$$

The equivalence ratio (Φ) is calculated using the following equation:

$$\Phi = \frac{1}{\lambda} \quad (5)$$

The loss of combustion is calculated by means of the flue gas temperature (T_f), the ambient temperature (T_p), and the CO_2 content in flue gases, as well as the ratio (0.65) present in the Siegert empirical formula [29], as follows:

$$q_A[\%] = \left(T_f[^\circ\mathrm{C}] - T_p[^\circ\mathrm{C}]\right) \cdot \left(\frac{0.65}{\mathrm{CO_2[\%]}}\right) \quad (6)$$

The combustion process efficiency is calculated using equation [26], as follows:

$$\eta_c[\%] = 100[\%] - q_A[\%] \quad (7)$$

3. Results and Discussion

The test results obtained for the first stage are presented in Figure 6, which depicts the change in the CO, NO_x, and PM emission and flue gas temperature (T_f) with reference to the excess air ratio (λ). According to the manufacturer's specification, the burner in its regular operation (with rated power) needs 100 m^3/h air maximally for the combustion process, which provides the maximum excess air ratio for such operation parameters of λ = 2.42.

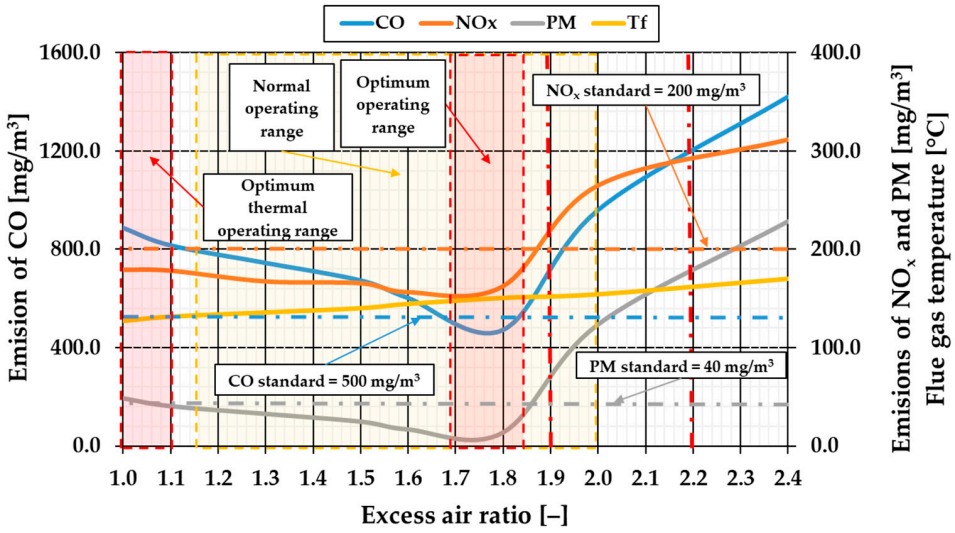

Figure 6. The course of the emission of harmful substances and temperature of flue gases in relation to the excess air ratio (λ) for the first test stage.

Figure 7 presents the course of the combustion process efficiency (η_c) and related loss of combustion (q_A) in relation to the excess air ratio. Figure 8 presents the course of emission of CO and NO_x and related combustion process efficiency (η_c) in relation to the excess air ratio for the first stage of research.

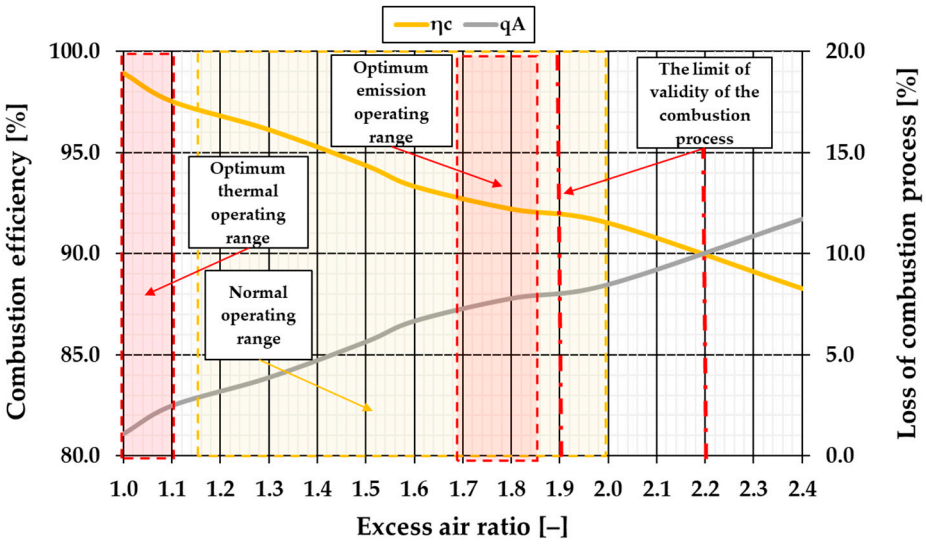

Figure 7. The course of the combustion process efficiency and loss of combustion in relation to the excess air ratio (λ) for the first test stage.

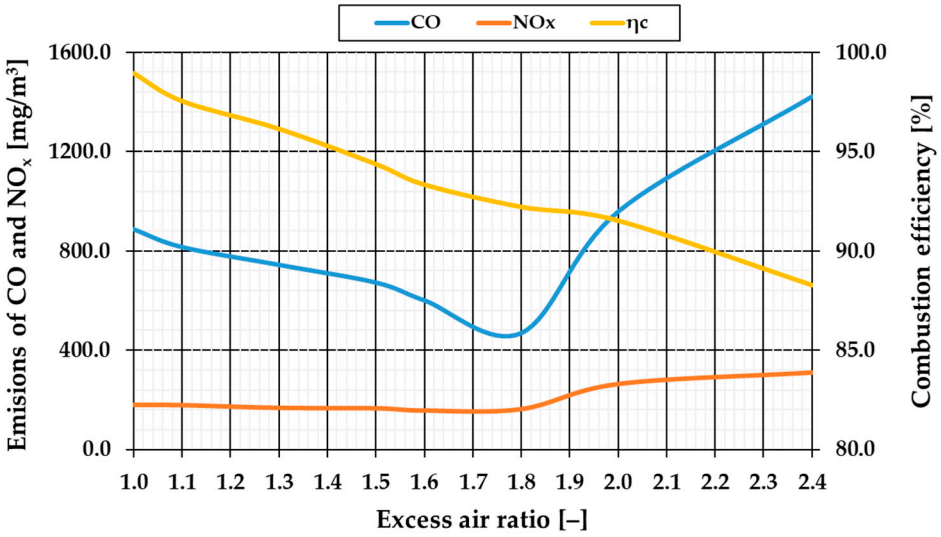

Figure 8. The course of the emission of CO and NO_x and combustion process efficiency in relation to the excess air ratio (λ) for the first test stage.

The test results obtained and their statistics are presented in Table 2.

Table 2. Test results for the first stage.

Excess Air Ratio	Measurement Value	CO	NO_x	PM	T_f	η_c	q_A
		mg/m^3 for 10% O_2 in Flue Gases			°C	%	
1.00	Average	887.19	179.47	48.44	127.18	98.93	1.08
1.10		815.82	178.54	40.54	131.49	97.53	2.47
1.30		744.25	167.61	32.64	135.80	96.13	3.87
1.50		672.78	165.75	24.74	140.11	94.36	5.64
1.60		601.31	156.68	16.84	144.42	93.33	6.67
1.80		470.44	162.60	13.53	150.54	92.21	7.79
2.00		959.04	265.14	123.34	154.25	91.52	8.48
2.40		1421.37	311.82	228.11	169.90	88.28	11.72

In the first test stage during combustion without air gradation the following regularities were observed:

- The normal boiler operating range for the settings of burner-rated power is within the excess air ratio range of λ = 1.15–2.00;
- The burner operating range within λ = 2.00–2.40 is present periodically in the stages preceding the application of a fresh fuel portion (in the combustion chamber of the burner), with a simultaneous abrupt increase in the air stream supplied for cleaning the combustion chamber from the post-combustion process residues;
- The burner operating range within λ = 1.00–1.10 is present periodically in the stages finishing the combustion of a given fuel batch and is related to a severe drop in flue gas temperature and related boiler heating power, which forces the control system to undertake actions to increase the power and which are related directly to the supply of a new fuel portion for combustion;
- The optimal operating range of the burner, in terms of low emission, falls within the range λ = 1.70–1.85, which allows it to satisfy all the requirements for emission parameters for solid fuel heating boilers combusting biomass; at the same time, the most optimal point is λ = 1.78, for which emissions are CO = 470.44 mg/m^3, NO_x = 162.60 mg/m^3, and PM = 13.53 mg/m^3 and the flue gas temperature is 150.54 °C;

- There was an increase in flue gas temperature observed, along with the increase in the excess air ratio in the combustion process.

When analysing the course of the combustion process efficiency and related loss of combustion in relation to the excess air ratio, the following regularities were observed:

- The range of the combustion process efficiency (η_c) of the burner falls within the following range: 98.93–88.28%;
- The range of the loss of combustion (q_A) of the burner falls within the following range: 1.08–11.72%;
- An increase in the loss of combustion was observed, along with an increase in the excess air ratio, simultaneously with a decrease in the combustion process efficiency arising from the excessive air stream supplied for combustion and the occurring adverse thermal phenomena contributing to the excessive emission of CO, NO_x, and PM.

When analysing both graphs, the following was observed:

- The limit value of the excess air ratio (λ) at which the pellet burner should operate is approximately $\lambda = 1.90$; above this value, there is an abrupt decrease in the combustion process efficiency, with its simultaneous decrease below the target value resulting from the valid standard [20]. At the same time, there is a violent growth in the loss of combustion, which contributes to the drop in the economic aspect of the performed combustion process, and there is a simultaneous severe increase in the emissions of all the registered harmful ingredients of flue gases;
- In the range of $\lambda = 1.00–1.10$, in which there is a stage finishing the combustion of a given fuel batch, the highest efficiency of the combustion process is obtained (at the simultaneous lowest loss of combustion); however, in this range, the emission of harmful substances, especially related to the combustion process stoichiometry (CO and PM) does not allow us to satisfy the assumptions of the valid standard [20]. This is caused by the radical decrease in the air stream supplied for the combustion process by the air supply system (switched off fan, only airflow to the combustion chamber forced by the stack draught), and there is a minor increase registered in the emission of nitrogen oxide (NO_x) caused by the occurrence of the phenomena of their rapid thermal formation activated by the heat transfer by the heated surfaces of the burner grate to the residues of fuel afterburned in its space;
- A burner operation period with an excess air ratio of $\lambda = 1.90–2.40$, usually in the phase preceding the application of a fresh fuel portion in the combustion chamber of the burner and the simultaneous execution of the burner cleaning process by increasing the airflow through the combustion and grate spaces of the burner (increasing the mass stream of the flowing air), causes a sudden increase in the emission of harmful substances generated by the solid substances (PM) floating from the burner grate and the cooling down of the combustion process, which is still taking place in the residues of smouldering biomass, resulting in excess carbon monoxide emissions (increased CO). Excessively supplied air flowing through the heated burner ducts removes excess heat from the burner surface (higher flue gas temperature), adversely affecting the formation of secondary nitrogen oxides (NO_x), especially in fast and thermal processes, which is also observed in the analysis of harmful substances exiting the boiler through the emitter.

This observation allows us to deem that the fuel loading change period related to the afterburning phase of the previously supplied fuel portion, together with the burner cleaning phase and the phase initiating the ignition of a fresh fuel portion, is indicated in the highest emission of harmful substances with the simultaneous severe change in thermal (efficiency and loss of combustion) and emission (wide range of the fluctuations of the excess air ratio) parameters. Furthermore, the burner operation area in the range of $\lambda = 1.90–2.20$ is an area that is feasible for the performance of the combustion process (e.g., for transient phases, loading of a new fuel portion or afterburning of the fuel being

combusted); nevertheless, on account of a serious disruption of the emission of harmful substances (its radical growth), it is a range that is not recommended for exploitation. Nevertheless, due to the automatic adjustment of the combustion process by systems based on heating medium temperature or oxygen content in flue gases [30], these parameters are frequently implemented during operation by objects exploited in real conditions, which is seen in the increase in emissions and the occurrence of problems connected with air quality (SMOG) on areas recognised as enclaves based on OZE [31]. Hence, there is a necessity for the modernisation of the currently used pellet burners for solid fuel heating boilers operating at an excess air ratio that is approximately $\lambda = 1.80$ higher through the reorganisation of the combustion process [32] or a change in the control system [30], for instance, by increasing the frequency of loading and afterburning phases, with a simultaneous decrease in fuel doses preventing the abrupt thermal impacts in the burner grate space.

The test results obtained for the second stage are presented in Figure 9, which depicts the change in the CO, NO_x, and PM emission and flue gas temperature (T_f) with reference to the excess air ratio (λ).

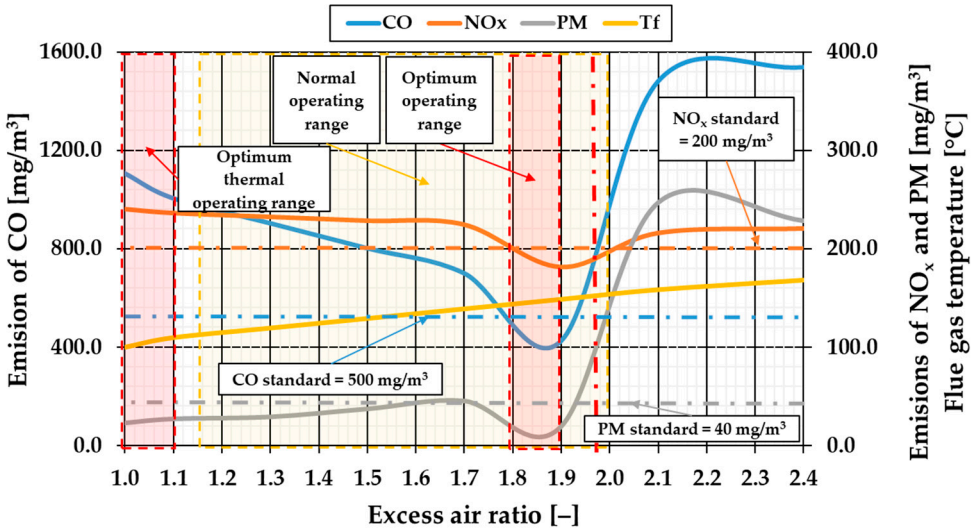

Figure 9. The course of the emission of harmful substances and temperature of flue gases in relation to the excess air ratio (λ) for the second test stage.

Figure 10 presents the course of the combustion process efficiency (η_c) and related loss of combustion (q_A) in relation to the excess air ratio. Figure 11 presents the course of emission of CO and NO_x and related combustion process efficiency (η_c) in relation to the excess air ratio for the second stage of research.

The test results obtained and their statistics are presented in Table 3.

Table 3. Test results for the second stage.

Excess Air Ratio	Measurement Value	CO	NO_x	PM	T_f	η_c	q_A
		mg/m³ for 10% O_2 in Flue Gases			°C	%	
1.00	Average	1107.13	240.47	22.44	100.15	97.20	2.80
1.10		1005.72	236.54	26.54	109.83	95.81	4.20
1.30		904.25	232.61	28.64	119.51	94.41	5.59
1.50		802.78	228.68	36.74	129.19	92.64	7.36
1.60		701.31	224.75	44.84	138.87	91.61	8.39
1.80		425.44	181.60	18.73	148.55	90.49	9.51
2.00		1480.04	216.14	246.34	158.23	89.80	10.20
2.40		1538.37	220.82	228.11	167.91	86.56	13.44

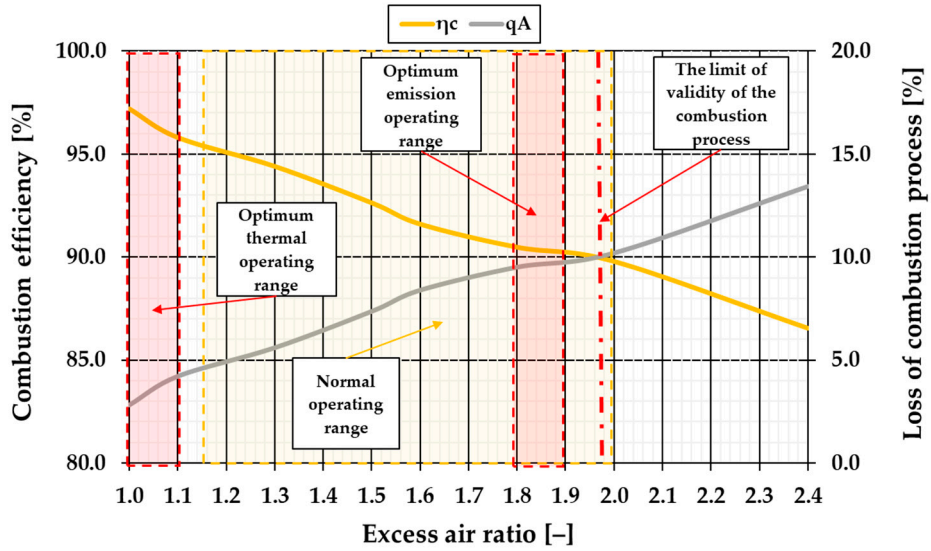

Figure 10. The course of the combustion process efficiency and loss of combustion in relation to the excess air ratio (λ) for the second test stage.

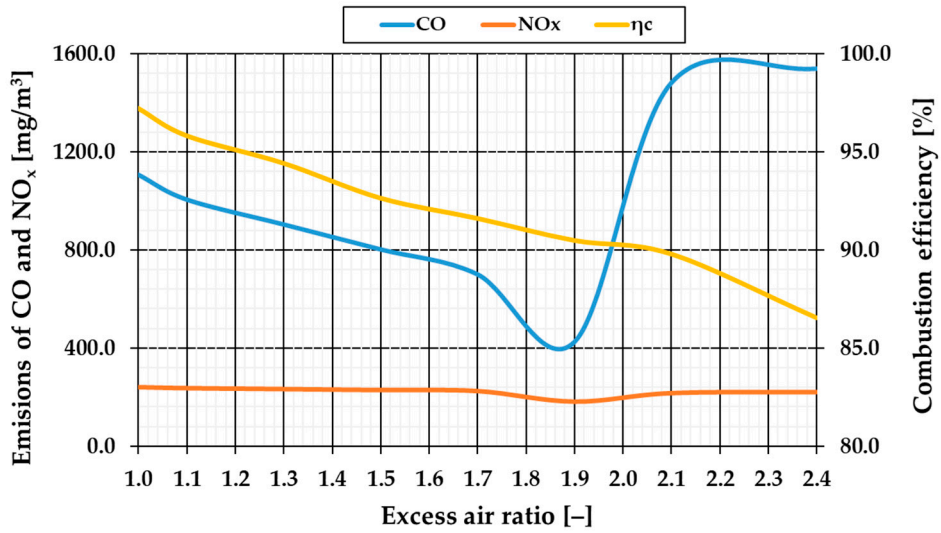

Figure 11. The course of the emission of CO and NO_x and combustion process efficiency in relation to the excess air ratio (λ) for the second test stage.

In the second test stage during combustion with air gradation, the following regularities were observed:

- The normal boiler operating range for the settings of burner-rated power is within the excess air ratio range of λ = 1.15–2.00;
- Periodical change stages of the excess air ratio preceding the application of a fresh fuel portion in the combustion chamber of the burner and finishing the combustion of a given fuel batch take place in identical operating ranges;
- The optimal operating range of the burner, in terms of low emission, falls within the range of λ = 1.80–1.90, which allows it to satisfy all the requirements for emission parameters for solid fuel heating boilers combusting biomass; at the same time, the most optimal point is λ = 1.88, for which the emissions are CO = 425.44 mg/m^3, NO_x = 181.60 mg/m^3, and PM = 18.73 mg/m^3 and the flue gas temperature is 148.55 °C;

- As for the process without air gradation for combustion, there was an increase in the flue gas temperature observed, along with an increase in the excess air ratio in the combustion process.

When analysing the course of the combustion process efficiency and the related loss of combustion in relation to the excess air ratio, the following regularities were observed:

- The range of the combustion process efficiency (η_c) of the burner falls within 97.20–86.56%;
- The range of the loss of combustion (q_A) of the burner falls within 2.80–13.44%;
- The shift in the intersection of the curves of efficiency and loss of combustion towards the normal operating range of the burner (λ = 1.15–2.00), with the simultaneous shift in that direction of the feasibility limit for the combustion process implementation, and the shift of thermal variables itself approaches positively towards the optimal operating range in terms of emission. Furthermore, this shift is demonstrated by the considerably lower emission of NO_x in relation to the burner operation without air gradation for combustion; in addition, the drop is 18.48% at an efficiency decrease of 1.72%, which results in an adverse increase in the emission of CO–54.33% and PM—99.72%, which suggests the oxygen deficiency of the zone finishing the combustion process (it is suggested to increase the share of the secondary air in the combustion process, but this process could contribute to the growth of NO_x emission in the secondary processes).

When analysing both graphs, the following was observed:

- The limit value of the excess air ratio (λ) at which the pellet burner should operate has increased and is approximately λ = 1.98, whereas, above this value, there is an abrupt decrease in the combustion process efficiency. At the same time, there is a violent growth in the loss of combustion, which contributes to the drop in the economic aspect of the performed combustion process and causes the simultaneous severe increase in the emissions. This differs from the combustion process without air gradation for combustion, which affects only flue gas ingredients directly related to the combustion process stoichiometry (CO and PM);
- As for the operation of the burner without combustion gradation in the range of λ = 1.00–1.15 with the stage finishing the combustion of a given fuel batch, it is connected with the highest efficiency of the combustion process and the simultaneous lowest loss of combustion; nevertheless, in this range, CO and NO_x emissions are higher than for the process without combustion gradation, and it does not allow the assumptions of the current standard [20] to be met, especially in the case of NO_x which, during combustion without air gradation, falls within this range of the excess air ratio in the standard;
- A burner operation period with an excess air ratio of λ = 1.90–2.40, usually in the phase preceding the application of a fresh fuel portion in the combustion chamber of the burner and the simultaneous execution of the burner cleaning process by increasing the airflow through the combustion and grate spaces of the burner (increasing the mass stream of the flowing air), causes a sudden increase in the emission of harmful substances related to the combustion process stoichiometry (CO and PM) generated by the solid substances (PM) floating from the burner grate and the distortion of the combustion process in the residues of smouldering biomass, resulting in excess carbon monoxide emission (increased CO) by blowing off the ends of the flame. However, unlike for combustion without air gradation for combustion, nitrogen oxide (NO_x) emissions increase slightly in relation to the optimal point (λ = 1.80–1.90) without exceeding the values obtained for the range of λ = 1.00–1.70, making it possible to reduce the emissions of such harmful substances in the crucial period of burner operation, which is not achieved in the standard operation of the device.

This observation allows us to deem that for the standard operation of the burner, the fuel loading change period related to the afterburning phase of the previously supplied

fuel portion, together with the burner cleaning phase and the phase initiating the ignition of a fresh fuel portion, is indicated in the highest emission of harmful substances, with a simultaneous severe change in thermal (efficiency and loss of combustion) and emission (wide range of the fluctuations of the excess air ratio) parameters. In the event of air gradation for combustion, the burner operation area in the range of λ = 1.90–2.20 is not a feasible area for the implementation of the combustion process due to the following reasons:

- Strong disruption of the emission of harmful substances (their radical growth);
- Operation beyond the range of the significant drop of the combustion process efficiency at the simultaneous significant increase in the loss of combustion.

This observation allows us to deem that in the case of the actual operation of boilers with burners with air gradation for combustion, it is necessary to optimise the boiler operation control systems (use individual control systems adapted to such operation) and, as far as necessary, to combine these systems with systems [32] for recording the continuous oxygen content in flue gases to improve the process of adjusting and controlling the operation of a boiler with the burner with air gradation for combustion. Another possibility for the optimisation of the burner operation with air gradation for combustion is changing the geometry of air supply channels in line with the burner optimisation method described earlier in this publication [33]. Gradation of the combustion air is also an essential process that should be carried out by a solid fuel boiler dedicated to domestic solutions (power not more than 50 kW) in the event of the further development of non-normative fuels, especially those based on domestic waste, which have high energy potential and can be an alternative, renewable energy source [34–36].

4. Conclusions

This publication concerns tests performed on the combustion process of wood biomass under the influence of air gradation for combustion. The tests carried out demonstrate that the combustion process under the influence of air gradation causes a change in this process by exerting a strong impact on the emission level of harmful substances. An advantageous decrease was observed in the emission of nitrogen oxides (NO_x), but on the other hand, the increase in the emission of carbon monoxide (CO) and particulate matter (PM) was noted, as well; furthermore, the change in the operation parameters was also recorded, which was highly dependent on the excess air ratio (λ). In the case of a combustion process without air grading, the optimum range for the excess air ratio (λ) in terms of emissions is between 1.70 and 1.85, enabling the boiler to meet the requirements of the current emission standards. In the case of the most optimal point (λ = 1.78), the emissions of the respective tested flue gas component are CO = 470.44 mg/m^3, NO_x = 162.60 mg/m^3, and PM = 13.53 mg/m^3. In the case of a staged combustion process, the optimal emission range for the excess air ratio (λ) is in the range of 1.80–1.90, and at the most optimal point (λ = 1.88), the emissions of the given test exhaust component are CO = 425.44 mg/m^3, NO_x = 181.60 mg/m^3, and PM = 18.73 mg/m^3. Comparing the optimum points of burner operation for operation with and without air grading, an increase of 12% in NO_x and 38% in PM and a decrease of 10% in CO were observed.

The excessive amount of carbon monoxide and particulate matter (mainly carbon black) generated in the combustion processes during air gradation can be reduced at the boiler level by using an afterburning chamber outside the main combustion chamber or ceramic catalytic inserts responsible for afterburning the residues of the non-stoichiometric combustion process [32].

Another feasible optimisation of the currently manufactured pellet burners with air gradation for combustion is the technical reorganisation of the air supply systems of the initial and final fuel combustion zones, the optimisation of the shape, size, and number of air supply channels, and the adjustment of the boiler operation adjustment system to the necessary management of not only thermal input of the device but also the emission of harmful substances generated inside them [33]. The size and number of ducts can affect the pressure of the metered air in the individual burner section (primary combustion zone

and post-combustion zone). With the burners currently designed and manufactured (such as the ECOMAT), the number of orifices used and their diameters are not an object of study for the effect of pressures or spray cooling on emissions. Analysing the results, there is no doubt that the effect of changing the combustion air supply location is due to a change in temperature (the temperature of the flue gases increases as the combustion air flow increases), which is directly related to the heat exchange processes taking place in the hot zones of the burner (the amount of heat received intensifies). Hence, it is necessary to undertake further research in the area of the influence of combustion air pressure or spray cooling on the degree of the formation of secondary harmful components of the flue gases and their emissions in the processes of the redistribution of combustion air carried out by pellet burners with low thermal output (up to 50 kW).

To conclude, as a group of relatively new devices, currently manufactured pellet burners with air gradation for combustion that are approved for the EU's market require further research and technical activities aimed at the optimisation of their design, and the main direction for further research works ought to be the optimisation of these designs to reduce the emitted harmful substances, which should be visible in the significant reduction of air pollution in the operation areas of such devices.

It has been shown that the implementation of combustion in low-power pellet burners (up to 50 kW) using only the technique of the gradation of combustion air increases the amount of emitted harmful substances associated with an incomplete or partial combustion process (CO and PM) that only reduces the formation and emission of nitrogen oxides (NO_x) through the formation of radicals. The emissions of products of incomplete combustion negatively affect both the economic and ecological effects of the combustion process. Hence, it is also necessary to undertake further research on the possibility of implementing the combustion process by grading fuel and air for the combustion process, with the aim of afterburning CO, soot, and carbon going into the ash and slag in the ash pan and exchanger sections of the boiler. This solution, however, will involve the installation of an additional secondary fuel feeding system in the boiler and the development of a post-combustion zone with an additional secondary air supply, which in the case of burners and boilers of small power (up to 15 kW for wood pellets), which are a very popular technical solution on the EU market, may not be possible, and the energetic use of biomass in combustion processes towards increasing their ecological use will require further design work or will be directed in another direction unrelated to the classical combustion process (such as biomass gasification).

Author Contributions: Conceptualization: B.C.; methodology: B.C.; software: B.C.; validation: B.C. and Z.N.; formal analysis: B.C.; investigation: B.C. and Z.N.; resources: B.C. and Z.N.; data curation: B.C. and Z.N.; writing—original draft preparation: B.C. and Z.N.; writing—review and editing: B.C. and Z.N.; visualisation: B.C. and Z.N.; supervision: B.C.; project administration: B.C. and Z.N.; funding acquisition: B.C. and Z.N. All authors have read and agreed to the published version of the manuscript.

Funding: The research was financed by the Poznan University of Technology's financial resources for statutory activity. Project numbers: 0712/SBAD/5252 and 0712/SBAD/5280.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

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

Nomenclature

C	carbon
CH_i	hydrocarbon radicals
CO	carbon monoxide

CO_2	carbon dioxide
HCN	hydrogen cyanide
N_2	nitrogen
NH_i	ammonia radicals
NH_3	ammonia
NO	nitric oxide
NO_2	nitrogen dioxide
NO_x	nitrogen oxides
O_2	oxygen
PM	particulate matters
T	temperature
T_f	exhaust gas temperature
λ	excess air ratio
τ	time
Φ	equivalence ratio

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