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A Second Wind: The Impact of Secondary Air Supply on Emissions and Efficiency of Sunflower Husk Pellet Combustion

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Abstract **– European Union recommends reducing high quality biomass usage in energy sector. Low quality biomass causes problems with combustion. Literature analysis indicates that secondary air usage can reduce ash agglomeration. Secondary air is implemented in this research to reduce ash agglomeration and increase the combustion time, simultaneously monitoring the effects on flue gas composition in the residential low-capacity retort pellet boiler. Secondary air was implemented in rotary air dispensary device, which induced swirl of flames. Reference tests were conducted to have comprehensive data of improvements. Secondary air supply was tested from 27.5 % to 45 % of the total supplied air, by adjusting the primary air supply amounts, thus reducing the oxygen concentration in the flue gases. Lowest secondary air supply had the best results out of all tests, which resulted in 2.9 % of efficiency increase, while CO emissions were reduced by 4.7 times compared to the best scenario of reference tests and NO_x emissions reduced 20 % compared to the same scenario. Secondary air implementation allowed the tests to last much longer than reference tests, since less airway blockage was occurring by ash agglomeration. This research indicates that low-quality biomass can be used in residential heating if proper technology is implemented in the pellet boiler, thus contributing in accordance with sustainable development goal 12: responsible consumption and production. Secondary air supply has a potential to reduce the ash slag formation, increase the combustion time and reduce the emissions produced.**

Keywords **– Air supply ratio; ash; ash agglomeration; emission; excess oxygen; flue gas; incomplete combustion; greenhouse gases; low-capacity boiler; regression; SDG.**

Nomenclature

CO	Carbon monoxide	ppm or mg/Nm^3
FT	Flue gas temperature	°C
LCB	Low capacity boiler	–
LQB	Low-quality biomass	–
NO_x	Nitrogen oxides	ppm or mg/Nm^3
O_2	Oxygen	%
PM	Particulate matter	mg/Nm^3
η	Efficiency	%

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1. INTRODUCTION

The European Union (EU) committed, under the 2015 Paris Agreement on Climate Change adopted at the 21st Conference of the Parties to the United Nations Framework Convention on Climate Change (COP21), to reduce greenhouse gas (GHG) emissions across all sectors. This commitment aims to keep the increase in the global average temperature well below 2 °C compared to pre-industrial levels [1].

1.1. Role of Biomass in Global Market

The cascade principle in biomass usage is crucial for achieving the EU's climate goals. To follow this principle, high-quality woody biomass (better suited for applications outside the energy sector) should be replaced by low-quality biomass (LQB) [2], [3], such as residues from various industries. In Latvia and other northern countries, the energy sector relies mainly on fossil fuels and woody biomass, including roundwood, fuelwood chips, and pellets [4]. However, these forestry products and byproducts have higher-value applications elsewhere: roundwood can be used in construction, fuelwood and sawdust in furniture and paper production, and only the remaining residues should be converted into pellets.

Biomass offers significant potential both for energy generation and for producing high-value products, as the annual accumulation of plant biomass exceeds the current global energy demand. While the global consumption of traditional solid biofuels such as firewood and charcoal has remained nearly constant, the use of wood chips and pellets for electricity (biopower), district heating, and residential heating has doubled over the past decade and is expected to continue growing [5]. Beyond wood-based bioenergy, biogas production from organic waste through anaerobic digestion is rapidly expanding in Europe and China, with the potential to replace up to 25 % of current natural gas consumption [6], [7]. If these trends continue, bioenergy could meet at least 30 % of global energy demand by 2050 [5], [8].

1.2. Issues Related to LQB Pellet Combustion

Biomass pellets usage as biofuel has become increasingly important in the industrial energy sector and district heating, especially as Latvia reduces its reliance on natural gas due to the current geopolitical situation. Locally produced biomass offers the most convenient alternative to natural gas; also, local producers can make pellets from various types of biomass and residues. Industrially designed heat plants adapt well to LQB and benefit from advanced economizers and flue gas treatment systems [9]. In contrast, individual heating systems often rely on high-quality biomass or even fossil fuels, as they use less advanced technologies. Studies by other authors point to the possibility of adapting existing boilers to LQB combustion [10]–[13]. The availability of LQB suitable for energy production in Latvia is significantly lower compared to wood-based biomass [14].

Conventional combustion of LQB generates high levels of GHG emissions. To address this, researchers have recently developed and tested technical approaches that reduce the negative impacts of LQB combustion to acceptable levels. GHG emissions depend directly on the combustion process, which is strongly affected by fouling and ash melting. Engineers can mitigate these issues by adding minerals or lowering the combustion chamber temperature. For example, kaolin and aluminum sulphate effectively reduce ash melting by lowering the concentrations of minerals and metals responsible for agglomeration. Similarly, dolomite and alumina can reduce agglomeration, although they are less efficient [15].

1.3. Role of Secondary Air in the LQB Pellet Combustion Process

Adding secondary air to the combustion process is an effective way to mitigate the negative effects of using LQB in boilers. Kardas *et al.* experimentally studied the implementation of secondary air in a residential pellet boiler with a thermal capacity of 18 kW, where the secondary air inlet was combined with the primary air inlet, limiting the ability to adjust each air supply independently [16]. The study focused on the height of the secondary air inlet above the burner, comparing two positions: 24 mm and 69 mm. The results indicated that the 24 mm height performed slightly better, although no intermediate heights were tested. The researchers emphasized that well-maintained and properly adjusted secondary air is crucial, as excessive airflow can cause flue gas backflow, negatively impacting boiler performance. They concluded that secondary air efficiency depends largely on a strong draft. The results showed that the 24 mm configuration achieved better carbon monoxide (CO) reduction. Furthermore, the authors noted that air oscillation contributes to the reduction of GHG emissions.

Bala-Litwiniak *et al.* studied both pine and sunflower husk (SH) pellets combustion with fuel feed rate of 0.883 kg/h and 1.028 kg/h, respectively. While air supply was 5.843 m^3/h and 6.869 m^3/h, respectively. Excess air in flue gases were around 8–9 % [17]. Authors also had a boiler with secondary air input, but since it had different aim of study, it was not focused on that, therefore no detail is provided.

Kirsanovs *et al.* tested a 25-kW pellet boiler, optimizing its performance using different air supply methods [18]. Authors examined two optimization strategies (flame spreading and flame concentration) to improve air–fuel mixing. Both approaches positively affected combustion, reducing CO emissions and thereby increasing combustion quality and boiler efficiency, with the greatest reduction achieved through flame concentration. The researchers also induced flame swirl to study its impact on combustion, which produced the most favorable results of all experimental setups. Based on these findings, authors recommended using more upward or perpendicular nozzle orientations to concentrate rather than distort the flame and confirmed that inducing swirl further improves combustion.

Carvalho *et al.* examined the combustion of various pellets made from agricultural residues in a 15-kW pellet boiler [19]. The study implemented a secondary air supply and an automatic ash removal system, but it still concluded that the boiler was unsuitable for some types of biomass. Tests were conducted for 8–12 hours under steady-state conditions. The researchers recommended implementing flexible control systems and automatic cleaning of the heat exchanger, as ash accumulation on the heat exchanger walls rapidly reduced boiler efficiency, particularly when burning agricultural biomass with high ash content. Even specifically adapted boilers encounter challenges with LQB, highlighting the need for further research in this field.

Venturini *et al.* compared ISO 17225-2 pellet classes, including the highest quality (A), lowest quality (B), and out-of-standard classes, by producing A-class pellets from high-quality softwood and adding fuelwood chips for B-class pellets [20]. Combustion tests with flue gas monitoring showed that CO and nitrogen oxide (NOx) emission factors were higher for lower-quality pellets due to incomplete combustion. The researchers manually monitored and controlled the air supply to optimize combustion, because the stove regulates pellets volumetrically via an auger screw. This system delivers different mass flow rates for pellets of varying densities, requiring adjustments in air supply for proper combustion. Each test was repeated by authors three times to reduce uncertainty, enhancing the scientific reliability of the results. Adjusting the air supply for each pellet sample ensured the most efficient combustion and increased the accuracy of the findings.

Ribeiro *et al*. tested the combustion of softwood pellets in an 18-kW pellet boiler, focusing on the effect of secondary air on sintered ash formation [21]. The results showed that higher temperatures inside the burner increased slag and agglomerated ash formation. The study also concluded that different ratios of primary to secondary air significantly affect ash melting. For their setup, the optimal air staging was approximately 30 % primary air and 70 % secondary air, though each boiler design may require different proportions. Combining swirl with secondary air improved flame stability and enabled efficient combustion by preventing blockage from ash agglomeration. The study further indicated that ash agglomeration is influenced by chemical elements and molecule formation, which depends on boiler temperatures and the vaporization of volatile species when secondary air is added. Overall, secondary air proved effective in reducing ash fouling and sintered ash formation. Since softwood pellets typically have a high ash melting point, the observed agglomeration suggests that the biomass used in the experiment may have been of lower quality.

Ash melting problem could be fully or partly solved, therefore reducing agglomeration, thus making LQB pellets suitable alternative combustible as wooden pellets, which has been addressed in several studies [18], [22]–[25]. Secondary air implementation can reduce clogging of airways in burner [21].

1.4. Nature of the Study

LQB has the potential to partially replace high-quality wood biomass in the energy sector, as agricultural residues are produced in large quantities and can serve as a wood substitute, allowing high-value wood to be used elsewhere. The increased use of woody biomass in energy generation has further driven interest in lower-quality biomass, a trend supported by the EU Renewable Energy Directive. In addition, growing energy demand and rising natural gas prices (exacerbated by Russian Federation aggression) have piqued interest in bioenergy.

LQB is a suitable substitute for fuelwood chips in industrial power plants, which benefit from technological advancements such as automatic ash removal, heat exchanger cleaning, and secondary and tertiary air systems, minimizing combustion issues. However, LQB is not recommended for low-capacity boilers (LCB), as these systems require frequent maintenance and present ash-related challenges for operators. Individual heating systems have limited technological capabilities to combust LQB efficiently, however, secondary air implementation may improve its suitability. Although extensive research has explored LQB usage in individual heating (focusing on emission reduction and ash management) this issue remains unresolved.

This study, conducted within the framework of the Bioenergy Observatory project, focuses on implementing secondary air for LQB pellet combustion. The research designs and tests an additional air supply (secondary air) to reduce clogging risks in biomass pellet boilers. The hypothesis is that secondary air will decrease fouling and ash agglomeration in the burner, reducing airway blockages and making combustion more efficient and environmentally friendly. Practical application of these findings could reduce the use of high-quality wood biomass in energy production and decrease fossil fuel consumption, particularly in individual heating systems. Therefore, this paper centers on evaluating secondary air implementation for LQB combustion.

2. METHODOLOGY

Fig. 1 illustrates the main steps of the research. The first step, "Selection of biomass pellets," involved choosing suitable pellet types. Industrially produced pellets, although appropriate for industrial use, often cause problems in residential combustion; therefore, the authors selected SH pellets for testing. The pellets had a diameter of 8 mm, while their length varied due to production specifics and the low lignin content of the biomass, resulting in reduced physical durability. Fuel parameters were analyzed in the RTU IESE Environmental Monitoring Laboratory ("Proximate and ultimate analysis" substep).

SH pellets were then subjected to preliminary combustion tests ("Initial findings and verification" substep), which revealed severe ash agglomeration issues, leading to increased emissions from incomplete combustion. The measured fuel properties were as follows: moisture content – 8.88 %, ash content – 3.08 %, physical durability – 97.8 %, bulk density – 720 kg/m³, gross calorific value – 20.08 MJ/kg, and ash melting temperature – 1042 °C. The calorific value corresponded to the chemical composition of the main energy components: C – 50.5 %, H – 5.9 %, N – 1.1 %, S – 0.05 %, and O – 42.45 %.

The pellet boiler GRANDEG BIO 25 kW served as the combustion plant during the "Combustion and monitoring" step and was inspected as part of the "Experimental setup preparation" step. The boiler has a cylindrical combustion chamber measuring 40 cm in diameter and 52 cm in height. The burner, located at the bottom of the chamber, is 13 cm deep with a diameter of 14.5 cm. The heat carrier volume of the boiler is 90 liters. The burner is a conventional wood pellet design with a nominal output power of 25 kW.

Air supply was measured using a Testo 440 DP airflow sensor, which was directly attached to the boiler's air inlet and outlet to ensure accurate data collection. However, this sensor was unsuitable for high-temperature measurements; therefore, no data were recorded during the combustion tests ("Equipment check tests" substep). The collected data were later used to calculate characteristic parameters and perform regression analysis during the "Data analysis and interpretation" step.

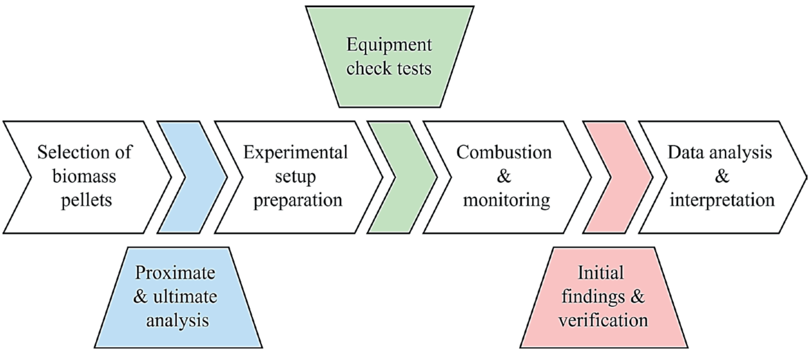

Fig. 1. Basic scheme of method used in research.

2.1. Experimental Setup

The experimental setup consisted of several steps that were essential for ensuring safety and proper combustion. A cold-water supply was provided to consume the heat produced, ensuring constant consumption and eliminating the possibility of overheating. The heated water was discharged as wastewater, resulting in no useful heat recovery; however, the combustion test results were considered very accurate and reliable, as only the boiler's efficiency was under investigation.

For all experiments, the pellet supply rate was fixed, ensuring a constant heat input rate. The feed rate was maintained within the range of 3.0–3.3 kg/h, with most tests recording

3.2 kg/h, which corresponded to approximately 16.4 kWh of thermal energy supplied to the burner.

Fuel was fed to the burner via an underfed auger screw, while primary combustion air (being the only originally implemented air source) was delivered through the same shaft as the pellets. Nevertheless, the air supply duct was kept fully separated from the pellet feed, minimizing premature mixing of fuel and air, which occurred only within the burner.

Although the air supply settings were not altered, the inlet airflow varied significantly depending on the conditions inside the burner. Back-drafting was observed, caused by ash melting, which restricted airflow and significantly influenced combustion. During one test, the inlet air had a volumetric flow rate of 29.5 m^3/h, whereas the outlet flow, with an empty burner, measured 23 m^3/h. When the burner was filled with pellets, the flow was reduced to 8.6 m^3/h. Back-drafting was observed to increase further during prolonged combustion, as slag formation progressively blocked the air channels, thereby inducing incomplete combustion.

2.2. Secondary Air Inlet Device Setup

High temperatures were present inside the burner; therefore, stainless steel was selected for the chamber's internal components. The device was used as an air supply unit, and the air was distributed through several nozzles that could be manually and individually adjusted, allowing the optimal air inlet to be controlled from multiple angles. This adjustment minimized the effect of unequal air distribution, where nozzles closer to the supply delivered more air than those on the opposite side of the ring. The design of the nozzles and the placement of secondary air are shown in Fig. 2. The covers of the nozzles could be bent to redirect and regulate the airflow through each nozzle.

The nozzles were positioned at an angle not directly aimed at the flame, thereby initiating rotation and creating a vortex effect that enhanced the mixing of combustion gases with air. Vertically, the nozzles were positioned at 90°, but during the tests they could be redirected upward or downward to modify air dispersion and turbulence. Nevertheless, downward positioning of the nozzles was discouraged [18].

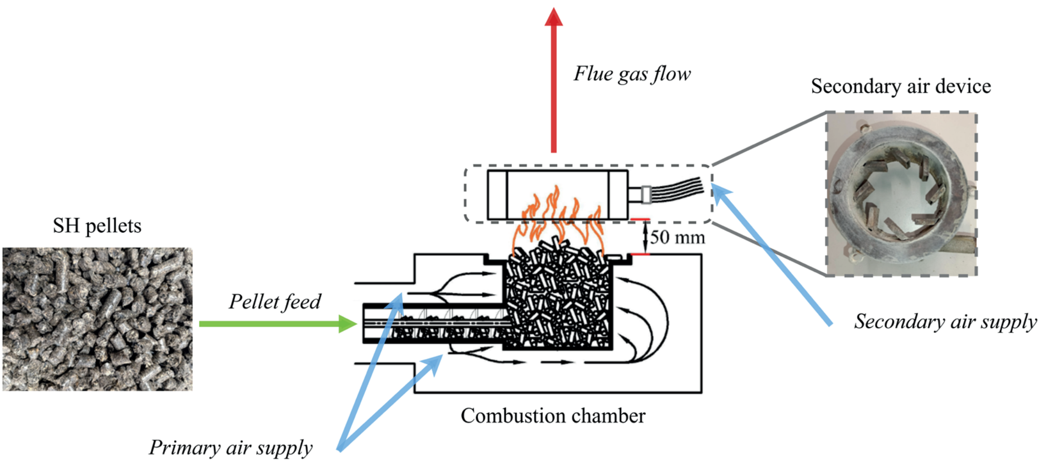

Fig. 2. Main processes and elements of experimental setup.

Such adjustments were found to improve flame stability, which is a key factor for achieving high combustion efficiency. Stable flames were less prone to extinction and oscillations, which was critical for maintaining consistent combustion. A swirl effect in the flame was induced, while secondary air was simultaneously introduced into the combustion zone. The air supply was connected to the automation system, enabling the inlet flow rate to be adjusted. Air was supplied in short pulses every few seconds, with timing specified by the operator.

The secondary air supply motor had a power of 0.09 kW, allowing an intake capacity of 74.4 m^3/h at maximum power. However, due to design flaws in the secondary air nozzles and the connection between the motor and the secondary air inlet device, significant backdraft and flow resistance were generated. As a result, the maximum achievable air flow into the combustion chamber was limited to 8.9 m^3/h. Consequently, adjustments of the air-to-fuel ratio were constrained mainly by the secondary air supply capacity.

Because the inlet nozzles were located above the burner, the secondary air was not obstructed by pellets or ash. Thus, ash and slag accumulation around the burner during combustion did not affect the secondary air supply. However, the secondary air flow was slightly influenced by the rise in the electromotor temperature. During continuous operation, the motor temperature reached approximately 80 °C, while operation at 75 % of rated power resulted in temperatures of around 65 °C.

Various primary air flow rates were measured, as the ash agglomeration exhibited non-linear and unpredictable behavior, gradually reducing the airflow delivered by the primary fans. Interaction effects and backdrafts were observed when both primary and secondary air fans operated simultaneously. Nevertheless, since secondary air was not in direct contact with the biomass, ash agglomeration did not affect its supply, which remained constant throughout the tests.

Combustion experiments conducted without secondary air were treated as reference tests and designated as REF1, REF2, and REF3. Different primary air supply rates were tested to identify the most optimal combustion process achievable with primary air alone, and three fan settings were evaluated (Table 1). Secondary air implementation involved two configurations. In the first configuration, the fan operated intermittently, turning on for 1000 ms and off for 1000 ms, delivering 6.8 m^3/h of air – approximately 75 % of the fan's maximum capacity. In the second configuration, the electric motor was operated on full power, enabling continuous operation and supplying 8.9 m^3/h of air. The relatively low air supply rate was attributed to the inadequate connection between the secondary air fan and the inlet device.

TABLE 1. EXPERIMENTAL PLANNING OF PRIMARY AND SECONDARY AIR VARIATIONS

	Primary air			**Secondary air**		
	ON, ms	OFF, ms	Supplied air, m^3/h	ON, ms	OFF, ms	Supplied air, m^3/h
REF1	100	3000	various	Off all the time		-
REF2	100	4000	various	Off all the time		-
REF3	100	5000	various	Off all the time		-
SA4	100	4000	various	1000	1000	6.8
SA5	100	5000	various	1000	1000	6.8
SA6	100	6000	various	1000	1000	6.8
SA7	100	5000	various	On all the time		8.9
SA8	100	6000	various	On all the time		8.9
SA9	100	8000	various	On all the time		8.9

The selected secondary air supply rates were intended to determine the optimal ratio between secondary and primary air. However, due to the suboptimal design of the secondary air system, only about 70 % of the theoretical maximum flow could be achieved. Even with the secondary air fan operating at its maximum capacity, the resulting air distribution reached approximately 40 % secondary air and 60 % primary air. The fan was controlled using a simple on/off (binary) approach, where 75 % of the nominal power was obtained by alternating 1000 ms of operation with 1000 ms of inactivity. This pulsed control created slight oscillations in the air supply, which is consistent with recommendations found in the literature.

For each experimental set (REF1–REF3, SA4–SA6, and SA7–SA9), the secondary air settings were kept constant, while the primary air settings were adjusted to achieve excess oxygen concentrations in the flue gases of 7.5 %, 9 %, and 10.5 %, respectively. These tests were designed to verify the findings of other studies, which suggested that optimal combustion efficiency is reached when excess oxygen in the flue gases is maintained at approximately 8–9 % [17].

3. Results

Experiments conducted by authors according to the established methodology provided results for CO, NO_x, particulate matter (PM), flue-gas temperature (FT), efficiency (η) and temperatures inside the boiler (t_{Burner}, $t_{Chamber}$, $t_{Exit\ chamber}$). Overall, the results indicated significant variations in combustion behavior. Most of these differences were associated with the application of secondary air, independent of the primary air ratio or excess oxygen levels in the flue gases. Nevertheless, optimization of both primary and secondary air ratios was identified as crucial for achieving the most efficient combustion process.

LQB, characterized by its high ash content and low ash melting temperature, caused the accumulation of ash and slag around the burner and airways, eventually resulting in blockage. While the ash in the combustion chamber had a relatively low density and could be displaced by the pellet feed and air supply, the slag forming inside the burner was considerably denser (Fig. 3, left) and progressively restricted the air supply during combustion.

Fig. 3. Slag formation inside of burner (left) and taken out of boiler (right) from reference tests.

CO and NO_x were considered the most critical indicators of proper combustion; therefore, this research primarily focused on these emissions. Both the average emissions and their variation over the duration of the tests were evaluated, as slag formation (Fig. 3, right) led to a notable increase in emissions. This effect was more pronounced in the reference experiments (REF1–REF3), whereas in tests with secondary air, such increases occurred after a longer operating period.

REF1, REF2, and REF3 were performed using only primary air. Consequently, slag formation in the airways directly impaired the combustion process by obstructing the air supply. The resulting oxygen deficiency led to elevated CO emissions (Table 3). Although the methodology specified a test duration of three hours, the reference tests were terminated after approximately one hour due to excessive CO emissions and complete flame extinction. Safety considerations were also taken into account when interrupting these experiments.

After the reference tests had been completed by the authors, secondary air was implemented, and additional tests were performed. The tests were found to be more complex than initially anticipated by the authors. The secondary air regimes were defined in the methodology prepared by the authors, which specified six secondary air tests. Each test was carried out with a predetermined air supply rate, representing a proportion of the total air input. As shown in Table 2, the proportion of secondary air ranged from 27.5 % to 45 % of the total air supplied.

TABLE 2. AIR SUPPLY AMOUNTS AND RATIOS

Experiment number	**Secondary air**		**Primary air**	
	Supplied air, m^3/h	supply ratio, %	Supplied air, m^3/h*	supply ratio, %
SA4	6.8	27.5	15.9	72.5
SA5	6.8	30	17.9	70
SA6	6.8	32.5	14.1	67.5
SA7	8.9	30	16.5	70
SA8	8.9	35	13.4	60
SA9	8.9	45	10.9	55

Note: Primary air supply is calculated from average values and are greatly varying during the tests, especially when ash agglomeration was blocking the airways.

In the literature analysis, the authors defined various air supply ratios, with the highest combustion improvement observed at a secondary air proportion of 70 % of the total air. However, this level could not be achieved in practice due to technological limitations. Nevertheless, multiple types of data could be analyzed using the implemented air supply regimes, including emissions and other boiler performance parameters (Table 3). The impact of slag formation on combustion was categorized as follows: 3 – high, 2 – medium, and 1 – low.

TABLE 3. MEASURED DATA OF THE EXPERIMENTS

	REF1	**REF2**	**REF3**	**SA4**	**SA5**	**SA6**	**SA7**	**SA8**	**SA9**
CO, mg/Nm^3	6642	7038	15144	1407	5447	5788	2697	3734	5641
NO_x, mg/Nm^3	280.8	292.0	134.8	238.6	158.4	178.0	265.3	194.2	125.9
PM, mg/Nm^3	171	148	154	263	226	77	83	123	57
FT, °C	89.9	86.8	84.3	75.7	79.6	71.6	96.1	96.8	97.3
t_{Burner}, °C	434	451	460	502	529	537	539	567	500
$t_{Chamber}$, °C	431	447	450	419	448	448	445	453	428
$t_{Exit\ chamber}$, °C	391	399	407	378	429	403	393	405	389
η (heat losses), %	88.1	88.9	87.0	91.8	90.2	90.5	89.4	89.6	89.4
η (direct), %	88.0	90.1	88.2	87.0	88.9	80.7	88.9	89.5	82.1
Slag formation	3	3	3	2	2	1.5	2	2	1.5

Efficiency, calculated by the authors directly from the useful heat generated, differed significantly from the efficiency determined based on heat losses. This discrepancy may have arisen from measurement inaccuracies or improper data handling. For subsequent comparisons, the efficiency calculated from heat losses was considered more reliable. Interestingly, some efficiency values were similar between methods, while others differed by several percentage points, as observed in tests SA6 and SA9. The data presented corresponded to the full duration of the tests, which lasted three hours; however, variations within the tests were notable, as they reflected observable trends as shown in Table 4. Negative values indicate a reduction of the parameter compared to the first and last hour, while positive values represent an increase.

TABLE 4. COMBUSTION PARAMETER CHANGE DURING THE TESTS

	SA4	**SA5**	**SA6**	**SA7**	**SA8**	**SA9**
CO	–42.3 %	38.3 %	157.3 %	41.9 %	71.3 %	–43.5 %
NO_x	–13.9 %	–11.4 %	1.5 %	9.9 %	9.2 %	9.2 %
Excess O_2	–4.8 %	–4.2 %	–3.9 %	0.5%	–3.3%	0.2%
t_F(FT)	–7.4 %	–9.4 %	–5.3 %	0.3 %	0.3 %	0.3 %
t_{Burner}	10.6 %	9.0 %	9.9 %	5.3 %	3.8 %	8.4 %
$t_{Chamber}$	–0.3 %	1.2 %	1.0 %	–0.1 %	2.6 %	1.0 %
$t_{exit\ of\ chamber}$	–2.5 %	–2.4 %	–1.3 %	2.5 %	–3.7 %	–2.5 %
Efficiency (η)	1.6 %	0.1 %	–0.9 %	–0.2 %	–0.6 %	0.4 %
Thermal heat losses	–12.2 %	–16.2 %	–11.1 %	0.7 %	–2.2 %	1.0 %
Chemical heat losses	–46.6 %	15.3 %	37.9 %	6.1 %	29.8 %	–15.6 %

Many variables are being measured and connected by authors to each other, which defines the whole combustion process; however, accurate prediction and forecasting are complex and can be used with empirical equations using *Statgraphics Centurion 19*. For each parameter, there is a different equation, since other variables influence specific characteristics of the combustion.

CO emissions are expressed with Eq. (1), which indicates the interconnection between main variables affecting the CO emission amount. CO is affected by secondary air and primary air, which decreases the amount of CO emitted, while burner temperature and chamber temperature are increasing the CO emissions:

$$CO = 21239.5 - 123.332 \cdot SA - 1858.84 \cdot O_2 + 5.2696 \cdot t_{Burner} + 1.486 \cdot t_{Chamber}, \quad (1)$$

where

CO carbon monoxide concentration in flue gases, mg/Nm^3;
SA secondary air proportion, %;
O_2 excess air concentration in the flue gases, %;
$t_{Chamber}$ temperature around the burner in the combustion chamber, °C;
t_{Burner} temperature in the burner, °C.

NO_x emissions are calculated using Eq. (2), which has 3 variables – temperature of the combustion chamber and burner and also O_2 concentration in flue gases. Chamber temperature has an increasing effect on the NO_x emissions, while burner temperature has decreasing effect on the NO_x emissions. As expected, O_2 has positive or increasing effect on the NO_x emissions:

$$NO_x = -790.056 + 1.95 \cdot t_{Chamber} - 0.447 \cdot t_{Burner} + 42.606 \cdot O_2, \quad (2)$$

where NO_x is nitride oxide emission concentration in flue gases, mg/Nm^3.

Efficiency (η) is expressed with Eq. (3), which indicates that lower CO emissions, lower O_2 concentration in flue gases and lower flue gas temperature is desired. Such conclusions were also logical according to the literature, since lower CO indicates better and more complete combustion, which reduces the chemical losses (Q_3). Reduced flue gas temperature also is desired, since less physical heat is lost due to the specific heat of flue gases (Q_2). Also reduced O_2 is desired because less air must pass through the combustion zone, thus reducing the physical heat of input air is reduced, therefore reducing the cooling, which is done by air supply:

$$\eta = 102.321 - 0.000461 \cdot CO - 0.5034 \cdot O_2 - 0.0684 \cdot t_F, \quad (3)$$

where

η efficiency of the boiler, %;

t_F flue gas temperature, °C.

These equations can be used to predict the values of said parameters; however, the correlation differs from parameter to parameter. Correlation coefficient of the CO emission prediction is 0.77, which indicates high correlation. Similarly, NO_x with correlation of 0.776. Efficiency has a very strong correlation, with correlation coefficient of 0.97. The use of empirical equations provides a convenient tool for predicting emissions and other boiler parameters, which can support economic analyses and other applications. However, due to the generosity of the pellet producer, the price of the pellets used in the experiments was not disclosed, as they were provided as a gift by the manufacturer.

4. CONCLUSION

Ash agglomeration during the combustion of low-quality biomass (LQB) pellets is the primary reason for increased emissions and decreased efficiency, and it requires further investigation. Literature analysis suggests that secondary air can potentially reduce greenhouse gas (GHG) emissions and slag formation during LQB combustion; however, reported results are not entirely consistent.

Secondary air implementation has the potential to increase combustion stability and quality by prolonging combustion time. It also reduces the likelihood of incomplete combustion, as air supply sources are separated. The results of this study demonstrate that secondary air improves combustion efficiency while significantly lowering carbon monoxide (CO) and nitrogen oxide (NOx) concentrations in the flue gases. Compared to the best-performing reference scenarios, CO emissions decreased from 6642 mg/Nm^3 to 1407 mg/Nm^3 in test SA4, NO_x decreased from 134 mg/Nm^3 to 125 mg/Nm^3 in test SA9, and PM emissions dropped from 148 mg/Nm^3 to 58 mg/Nm^3 in test SA9. Test SA4 achieved CO emissions of 1407 mg/Nm^3, NO_x emissions of 238 mg/Nm^3, and PM emissions of 263 mg/Nm^3 – values that are comparable to those produced by premium-quality wood pellets. These findings suggest that secondary air implementation can bring LQB combustion closer to the emission levels of higher-quality fuels, although further research is recommended.

The highest combustion-zone temperatures were observed in test SA8, while flue gas temperatures were lowest in test SA6 (71.6 °C compared to 84.3 °C in REF3). The highest efficiency was achieved in test SA4 (91.4 %), compared with only 88.9 % in REF2. Visual observations during the tests indicated reduced slag formation in SA6 and SA9, likely due to lower air supply rates in the combustion chamber.

Overall, the results confirm that combustion is a complex physio-chemical process, significantly affected by secondary air implementation, which alters emission profiles and the chemical mechanisms of ash slag formation. These findings apply to the specific conditions and pellet types tested and should not be generalized without further validation. Based on the data collected, efficiency can be accurately calculated and predicted using flue gas temperature, oxygen concentration, and CO concentration. CO and NO_x emissions can also be predicted using empirical regression equations, though with lower accuracy.

Regression analysis revealed that each parameter is influenced by different variables. Efficiency showed the strongest correlation (determination coefficient is 0.97) and was negatively affected by CO and O_2 concentrations in the flue gas as well as by flue gas temperature. CO emissions were positively correlated with burner temperature but reduced by higher secondary and primary air supply rates. Conversely, NO_x emissions were positively correlated with O_2 concentration and combustion chamber temperature but decreased with higher burner temperature. These equations provide valuable guidance for future boiler design and optimization by quantifying the influence of each parameter on combustion performance.

The secondary air device examined in this study was a prototype, and further research is necessary to better understand its effects and optimize its performance. Experimental results showed that the secondary air inlet device and fan could not provide the planned 70 % of total air supply, highlighting a design limitation that should be addressed in future development.

Additional technological improvements should be considered in combination with secondary air implementation to enhance the performance of residential pellet boilers. LQB combustion in residential heating systems should be more strictly regulated due to its elevated emissions and potential safety risks. Future studies should also account for current energy trends, as electricity-based heating solutions are gaining wider adoption and could influence the relevance of LQB combustion in the residential sector.

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