



This is an open access article distributed under the terms of the Creative Commons Attribution 4.0 International License (CC BY 4.0), which permits use, distribution, and reproduction in any medium, provided the original publication is properly cited. No use, distribution or reproduction is permitted which does not comply with these terms.

OPTIMIZING COMBUSTION PROCESS: THE IMPACT OF FLAME ZONE AIR SUPPLY ON EMISSIONS AND PERFORMANCE IN PELLET BOILER




Alexander Backa^{1,*}, Nikola Čajová Kantová¹, Peter Hrabovský¹, Pavol Belány¹, Róbert Cibula², Sławomir Śladek³


¹University of Zilina, Research Centre, Zilina, Slovakia

²University of Zilina, Faculty of Mechanical Engineering, Department of Power Engineering, Zilina, Slovakia

³Silesian University of Technology, Department of Thermal Technology, Gliwice, Poland

*E-mail of corresponding author: alexander.backa@uniza.sk

Alexander Backa  0000-0003-0911-6678,
Peter Hrabovský  0000-0002-8425-6657,
Robert Cibula  0000-0003-1107-4147,

Nikola Cajova Kantova  0000-0002-7529-036X,
Pavol Belany  0000-0002-8313-9432,
Sławomir Śladek  0000-0003-2994-3734

Resume

Biomass combustion is a widely used renewable option for a small-scale heat and power, but incomplete burnout and pollutant formation remain challenges in boilers without optimized air staging. In this study, is investigated how controlled transport of air into the flame zone, implemented with an auxiliary tertiary system, affects performance and emissions in a bottom-fed pellet boiler. Tests were performed at constant fuel feed and primary/secondary airflow, with tertiary air varied between 0 and 15.8 m³/h. An airflow of about 8.9 m³/h proved optimal, giving the highest thermal output, a more uniform temperature distribution, and a nearly twentyfold reduction in CO emissions normalized to 10% O₂. NO_x rose only moderately (by approximately 60 mg/m³). The findings show that targeted air transport and staging into the flame zone can substantially improve combustion completeness and boiler efficiency.

Article info

Received 19 September 2025

Accepted 17 December 2025

Online 28 January 2026

Keywords:

combustion
pellet boiler
air supply
biomass
emission reduction

Available online: <https://doi.org/10.26552/com.C.2026.016>

ISSN 1335-4205 (print version)

ISSN 2585-7878 (online version)

1 Introduction

The biomass remains the sole renewable carbon-based fuel, and among thermochemical conversion technologies, combustion stands out as a dependable method for producing both heat and electricity. Over the past two decades, solid biofuels, particularly pellets, have emerged as one of the fastest-growing energy sources. However, many combustion systems were originally engineered for coal or fossil fuels and thus often suffer from poor control and incomplete burnout. In contrast, boilers specifically designed for biomass can extract energy more efficiently and lower pollutant emissions [1-2]. The growing focus on energy efficiency and emission reduction across all the sectors of transport and power generation underlines the importance of sustainable fuels such as biomass in the broader energy transition [3-6].

The combustion dynamics of pellet boilers are influenced by numerous variables [7]. Fuel quality

characteristics, such as pellet uniformity, moisture content, and composition, significantly affect gaseous emissions and particulate matter (PM) formation. For instance, studies have shown that high moisture content can increase emissions of CO, PAHs, and PM by factors of two to five, compared to drier fuel [8-9]. The fuel type, pre-treatment methods, and geometry also play a role in combustion efficiency and emission profiles [10-12]. Research further indicates that variations in feedstock composition, such as higher bark or agricultural residues, can alter the ash behavior and emission tendencies, while the application of mineral additives may improve fuel quality and stability during combustion [13-15].

Additionally, process dynamics during different combustion stages critically influence the pollutant release. Nussbaumer et al. (2008) observed that nearly half of total PM emissions can occur during the startup phase, which typically comprises only a small fraction of the cycle [16]. Fachinger et al. (2017) noted that both excessively low and high combustion velocities lead

to elevated emission factors. Ignition strategy further impacts outcomes: top-down ignition methods reduce PM emissions by 50-80% relative to conventional bottom ignition [17].

Efficient pellet combustion relies not only on the overall air-to-fuel ratio but on the spatial and temporal distribution of the supplied air, as well [7]. The combustion chamber typically receives air through three distinct streams: primary, secondary, and tertiary. Each of these inlets serves a specific function in the combustion process. The primary air is generally introduced beneath the fuel bed, where it promotes the initial stages of drying and devolatilization. Proper control of this stream is critical, as an insufficient supply can lead to incomplete oxidation of volatile compounds, whereas an excess may lower combustion temperatures and reduce efficiency. The secondary air is directed above the fuel bed into the region where volatile gases are released. Its role is to ensure thorough oxidation of these gases, thus minimizing unburned hydrocarbons and carbon monoxide. Optimizing secondary air distribution enhances flame stability, promotes complete burnout, and contributes to lower emission factors. The tertiary air, more commonly applied in larger and high-output boilers, is injected further downstream into the flame path. This airflow supports the final stage of oxidation, preventing the escape of unburned gases and fine particulates. Moreover, the strategic use of tertiary air helps maintain cleaner surfaces in the combustion chamber and the flue gas path by reducing soot deposition [18]. Complementary measures, such as compact cyclones or other dust separators, are often applied downstream to further reduce fine particle emissions, supporting overall system efficiency and compliance with emission limits [19].

Recent investigations have demonstrated that the redistribution of combustion air across these stages can substantially alter both emission profiles and thermal efficiency. Studies by Regueiro et al. showed that inadequate staging, where only primary air is used, results in particulate concentrations exceeding 360 mg/Nm³ at 6% O₂ [20]. In contrast, staged air injection with appropriate secondary and tertiary airflows reduces particulate levels to as low as 15-75 mg/Nm³ under similar conditions, though it may influence NO_x and CO formation differently. Other research confirms that dynamic control of air staging, adjusting the proportion and injection points during various combustion phases, can further optimize combustion, reducing CO and PM while maintaining high boiler performance [21-23]. These developments strongly indicate that optimizing the air-

fuel distribution, particularly the injection location and staging of flame-zone air, provides a promising pathway to enhance combustion completeness, reduce harmful emissions, and improve boiler thermal efficiency. Building on these insights, Backa et al. reported that in automatic boilers with bottom fuel feeding and without direct air supply into the flame region, elevated CO concentrations were observed even in the upper flame layers, whereas NO_x emissions remained relatively constant across the flame profile [24-25].

To address this limitation, an auxiliary tertiary air supply system was developed to introduce the combustion air directly into the flame zone, thereby improving the mixing of CO with O₂ and promoting its oxidation to CO₂.

The objective of the present research therefore was to examine the influence of the flame-zone air injection strategies on emission reduction and combustion performance in small-scale pellet boilers. Specifically, the study aimed to quantify how adjustments in flame-zone air staging affect CO, NO_x, and overall heat output to water, building upon both classical literature and the most recent experimental and numerical findings.

2 Materials and methods

In this section is described the experimental approach used to evaluate the influence of auxiliary air injection into the flame zone on boiler performance and emissions. The tests were carried out at constant fuel feed and constant primary/secondary airflows, while the tertiary airflow was varied in defined steps. In addition to heat output and temperature distribution in the combustion chamber, the main flue-gas components were continuously measured.

2.1 Experimental setup

The experiment was conducted on an automatic pellet-fired boiler with bottom fuel feeding (LOKCA USPOR) with a nominal rated output of 18 kW. However, since the unit represents an older type of appliance, its real achievable capacity was lower; the maximum measured output was approximately 15 kW. This type of combustion device is still relatively common in the regional market of Eastern Europe [26]. The fuel used in this study was spruce wood pellets certified to ENplus A1 quality. The proximate and ultimate analyses of the fuel are summarized in Table 1.

Table 1 Proximate and ultimate analyses of used wood pellets (*O₂ content was calculated by difference)

Volatile Matter	Fixed Carbon	Moisture	Ash	
77.13	16.95	5.56	0.36	
Carbon	Hydrogen	Nitrogen	Sulfur	Oxygen*
50.43	6.61	< 0.04	0.12	42.47

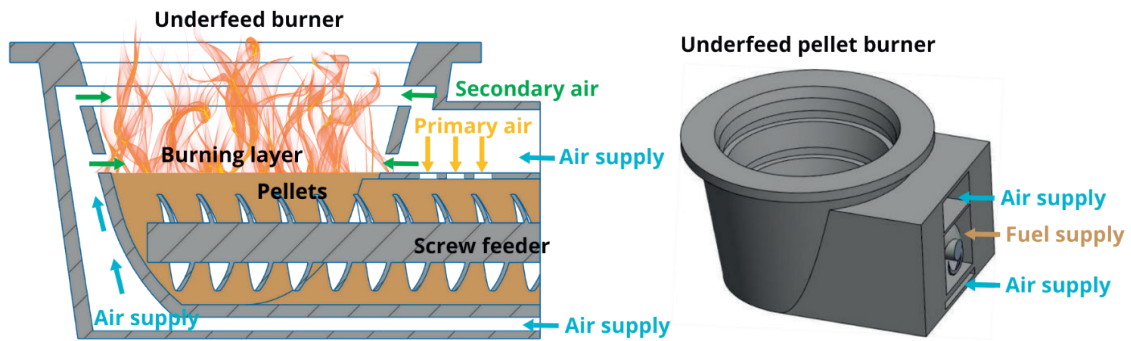


Figure 1 Method of air supply to the combustion chamber through a bottom-fed burner (before the modification)

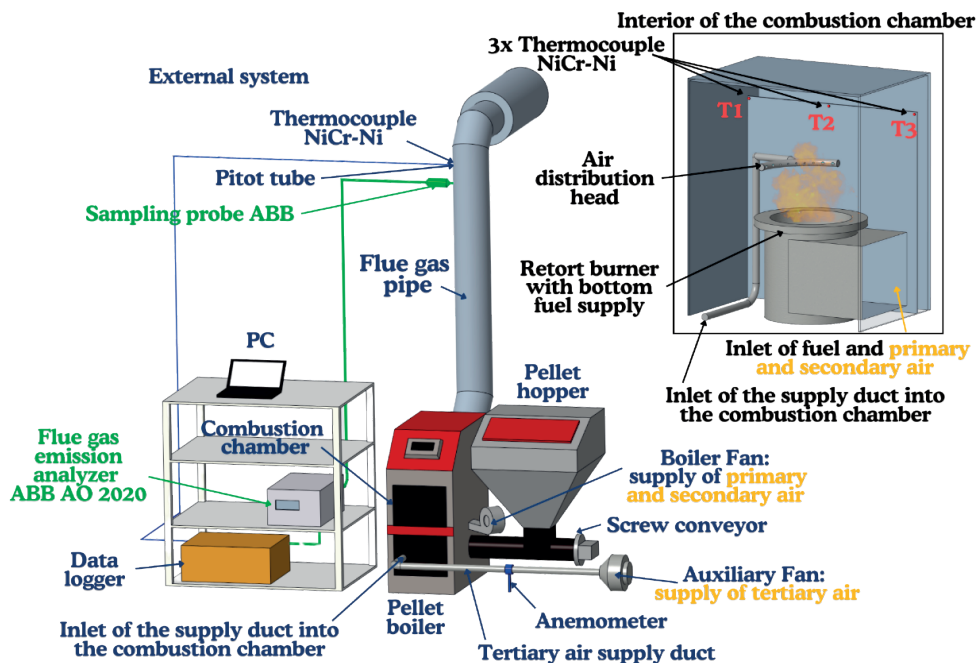


Figure 2 Experimental setup (external system and combustion chamber after the modification)

The pellets were automatically transported from the fuel hopper into the retort burner by means of a screw conveyor, operating in 18-second feeding cycles followed by 25-second pauses, resulting in a steady fuel supply of approximately 5.8 kg/h. The boiler fan provided a fixed combined primary/secondary air supply corresponding to a mass flow rate of 63.3 kg/h. The chimney draft was kept constant at 12 ± 2 Pa, in accordance with the STN EN 16510-1 requirements [27]. The draft was monitored with a differential pressure sensor, featuring a maximum measuring span of 0-100 Pa and an accuracy of 0.5%. In addition, the flue gas temperature inside the chimney was continuously recorded using a NiCr-Ni thermocouple.

2.2 The tertiary air supply

Originally, the boiler was equipped only with the combustion fan supplying a combined stream of primary and secondary air (Figure 1).

Following the findings of earlier studies, a system for the delivery of additional tertiary air was implemented. A schematic diagram of the combustion device, including the arrangement of the tertiary air supply, is shown in Figure 2.

Figure 3 shows the real experimental setup used to supply the tertiary air, with detailed views of the air duct and the combustion chamber.

Measurements were carried out under the constant primary and secondary air supply, while varying the tertiary air flow. The air distribution into the flame zone was provided by a manifold with nine orifices, whose diameters increased gradually from the center towards the periphery, with the central opening having a diameter of 6 mm and rising by approximately 5-10% outwards from one orifice to the next (Figure 3). The tertiary air jets were directed perpendicularly against the natural upward flow of the flue gases, to enhance mixing while minimizing the penetration into the fuel bed, which could otherwise cause an undesirable release of particulate matter.



Figure 3 Real experimental setup for the tertiary air supply:
a) overall system, b) air duct detail, and c) combustion chamber view

The transport of tertiary (auxiliary) air was ensured by an external fan equipped with a frequency converter, allowing adjustment of the rotational speed and thus the delivered air volume. The air was conveyed through a metal pipe with an inner diameter of 17 mm, into which the FVAD 15 MA1 anemometer was installed to measure the flow velocity. Based on the recorded velocity data (v), the volumetric airflow was calculated. The anemometer provided a measurement accuracy of $\pm 0.5\%$ of the sensor's final value and $\pm 1.5\%$ of the measured value. From this point, the system continued through a metal pipe section and a $\frac{3}{4}$ " flexible tube connected to the distribution head. The head consisted of a bent pipe with evenly drilled openings whose diameters gradually increased from the center toward the edge, thereby supplying the main tertiary air stream through the central openings while ensuring a uniform distribution across the flame zone.

A series of tests was performed with the tertiary air flow rates of 0, 3.73, 8.92, 13.4, and 15.82 m³/h. Each measurement lasted 30 minutes and was started only after the O₂ concentration, thermal output, and temperatures had stabilized. At the top of the combustion chamber, just before the heat exchanger section, three NiCr-Ni thermocouples (T₁-T₃; see Figure 2) recorded temperatures to monitor changes in the distribution of hot gases prior to and after the optimization.

2.3 Emission measurements

The analysis of flue gases was carried out using an ABB AO 2020 system. This device was fitted with the Uras 26 infrared module, which enabled continuous monitoring of carbon monoxide, carbon dioxide, nitrogen oxides, and sulfur oxides, with a measurement uncertainty below 1%. Oxygen concentration was determined with the Magnos 206 module, offering a precision of $\pm 0.5\%$.

Concentrations of the monitored components were initially logged in parts per million (ppm). For further evaluation, the values were recalculated to mg/Nm³ in accordance with STN EN 16510-1 [27], as expressed in Equation (1).

$$CO_{10\%O_2} = CO_{ppm} \cdot d_{CO} \cdot \frac{21 - 10}{21 - O_2} \quad (1)$$

In Equation (1), CO_{10%O₂} represents the standardized carbon monoxide concentration at 10% O₂, CO_{ppm} is the measured concentration in ppm, d_{CO} (kg/m³) is the density of carbon monoxide, and O₂ is the measured oxygen concentration (%). The normalization of emission values to 10% O₂ is consistent with the requirements set by Commission Regulation (EU) 2015/1189, which defines the eco-design criteria for solid fuel boilers of this type [28].

The same conversion procedure was applied for

nitrogen oxides, while the formation of sulfur oxides was negligible since the tested biomass fuel did not contain sufficient sulfur to produce detectable SO_x emissions.

3 Results and discussion

The temperature distribution in the upper part of the combustion chamber before the heat exchanger section revealed that even under the baseline conditions without tertiary air supply the system exhibited significant non-uniformity (Figure 4 and Table 2). The measured temperatures ranged from 587 °C at T1 down to only 463 °C at T3, clearly indicating uneven mixing of hot gases and the presence of colder flue gas in volume.

Such irregularities in temperature stratification are typical of older pellet boiler designs without optimized air staging, where the incomplete mixing and insufficient oxygen supply in the upper flame layers lead to unstable combustion zones [29]. With the addition of tertiary air, these temperature discrepancies were partly alleviated. The most uniform distribution was observed at a tertiary airflow of 8.92 m³/h, where the temperatures across the measurement points converged to 598 °C at T1 and T2, and 549 °C at T3. This more balanced profile reflects improved mixing of unburnt gases with oxygen in the

flame zone, thereby enhancing oxidation processes and stabilizing combustion. However, at higher tertiary airflows (13.4 and 15.8 m³/h), the distribution again became less balanced, suggesting that excessive air injection may disturb the flame stability and cool localized regions, thereby weakening combustion intensity. Comparable findings were reported by Kardas et al. (2024), who demonstrated that while separating combustion air into multiple stages reduced the CO emissions and improved flame oxidation, overly large secondary air supply decreased overall combustion efficiency due to excessive dilution and cooling of the reaction zone [30].

The boiler output and gas composition trends further support this interpretation (Figure 5 and Table 3). With increasing tertiary air supply, the flue gas oxygen concentration gradually rose from 11.68% to 13.92%, while CO₂ content decreased from 9.19% to 6.76%, indicating excess air conditions. The maximum water heat output of 11.33 kW was achieved at 8.9 m³/h, indicating that this setting provided the most favorable balance between the fuel feed and oxygen availability.

Further increases in tertiary airflow slightly reduced the boiler heat output, confirming that the excess air no longer contributed to combustion but instead reduced flame temperature and efficiency. These

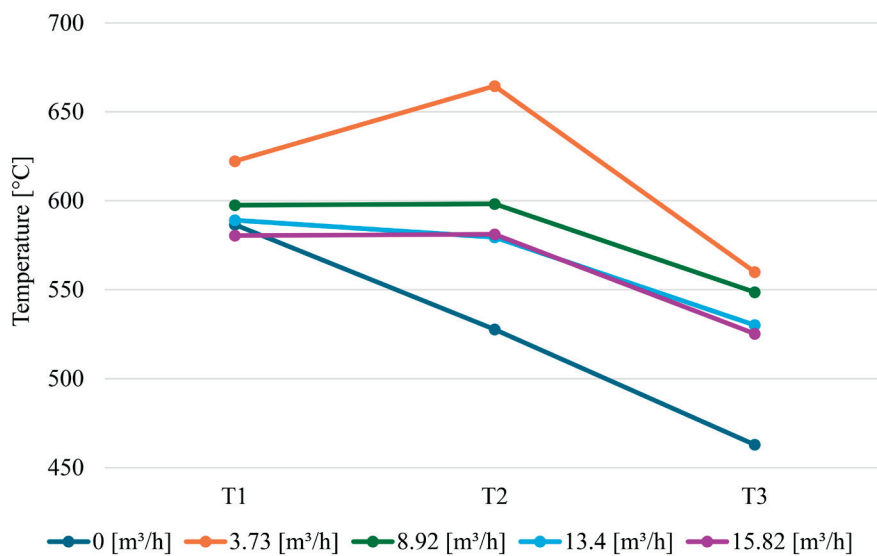


Figure 4 Temperature distribution in the upper part of the chamber with and without the tertiary air supply

Table 2 Effect of tertiary air supply on temperature distribution in the upper part of the chamber

Tertiary air flow rate	Thermocouple position		
	T1	T2	T3
0 [m ³ /h]	587	528	463
3.73 [m ³ /h]	622	665	560
8.92 [m ³ /h]	598	598	549
13.4 [m ³ /h]	589	580	530
15.82 [m ³ /h]	580	581	525

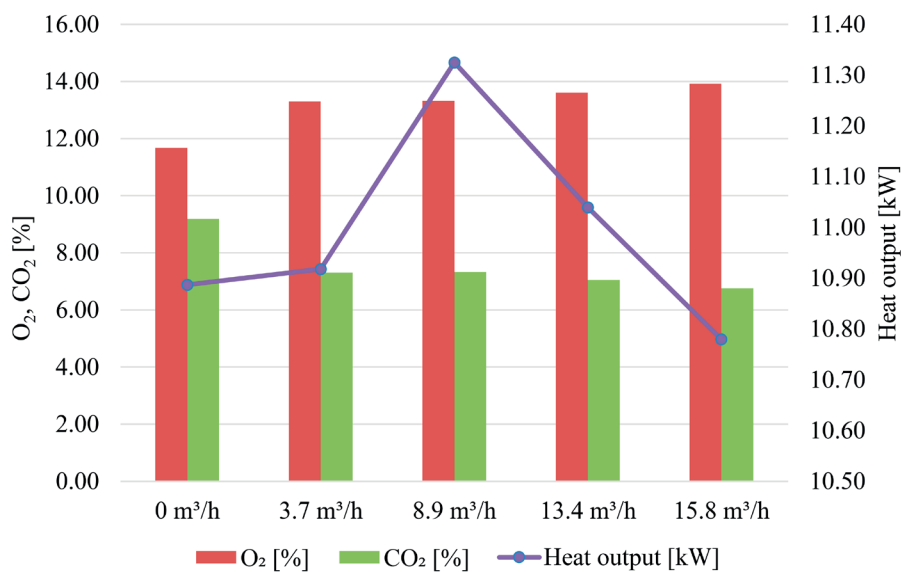


Figure 5 O₂, CO₂ and boiler heat output at different tertiary air flow rates

Table 3 Measured values of O₂, CO₂ and boiler heat output for different tertiary air flow settings

Parameter	Tertiary air flow rate				
	0 m ³ /h	3.7 m ³ /h	8.9 m ³ /h	13.4 m ³ /h	15.8 m ³ /h
O ₂ [%]	11.68	13.30	13.32	13.61	13.92
CO ₂ [%]	9.19	7.31	7.33	7.05	6.76
Heat output [kW]	10.89	10.92	11.33	11.04	10.78

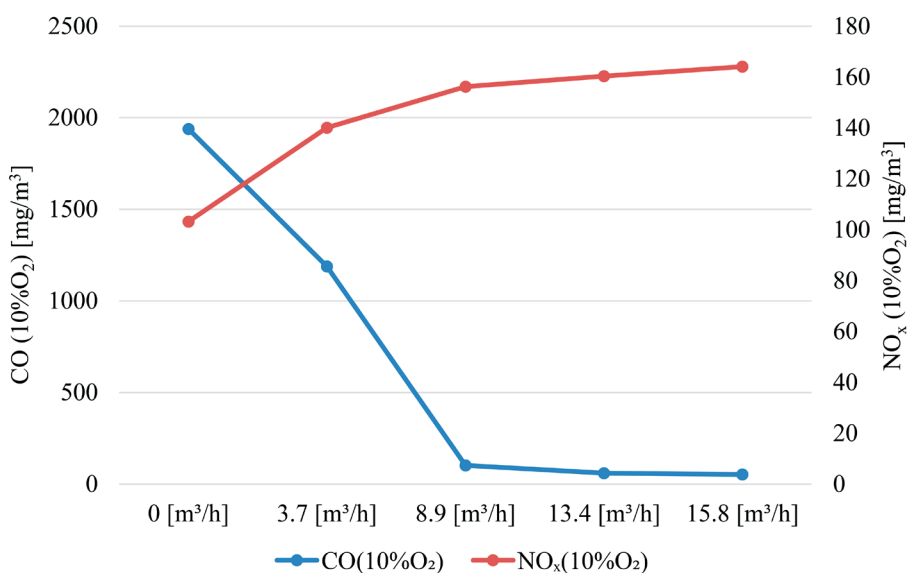


Figure 6 The CO and NO_x levels (normalized to 10% O₂) at different tertiary air flow rates

Table 4 CO and NO_x concentrations (normalized to 10% O₂) at various tertiary air flow rates

Parameter	Tertiary air flow rate				
	0 m ³ /h	3.7 m ³ /h	8.9 m ³ /h	13.4 m ³ /h	15.8 m ³ /h
CO(10%O ₂)	1939	1189	103	59	53
NO _x (10%O ₂)	103	140	156	160	164

results demonstrate that in boilers without the direct flame-zone air supply adjusting only the primary and secondary airflows is insufficient to achieve comparable thermal performance or to reduce CO to low levels, thus highlighting the critical role of targeted tertiary air [24].

The effect of tertiary airflow on emissions was the most striking for carbon monoxide (Figure 6 and Table 4).

At baseline, CO concentrations normalized to 10% O₂ reached 1939 mg/m³, indicating highly incomplete combustion. With progressive addition of tertiary air, the CO levels decreased sharply, dropping to 1189 mg/m³ at 3.7 m³/h and reaching only 103 mg/m³ at 8.9 m³/h, which corresponds to nearly a twentyfold reduction compared to the zero-air case. Further increases to 13.4 and 15.8 m³/h yielded only marginal CO decreases (59 and 53 mg/m³, respectively), while the boiler output has declined. This strong reduction demonstrates that targeted air staging is highly effective in promoting the oxidation of CO into CO₂, thereby completing the combustion process. Comparable reductions have been documented in earlier staged-air investigations, such as Zandekis et al. (2013), [29] and Ciupek et al. (2024) [31], who also observed substantial decreases in CO when optimizing staged or graded airflow supply in pellet boilers. At the optimal setting of 8.9 m³/h, the boiler also achieved its highest efficiency, improving by about 2% compared to baseline. It should be noted that the optimum tertiary-air setting reported here is specific to the tested fuel and the baseline primary/secondary air configuration; changes in the fuel type/moisture or in the primary/secondary air settings may shift this optimum.

While this condition minimized the CO emissions, NO_x normalized to 10% O₂ rose moderately, from 103 mg/m³ without tertiary air to 164 mg/m³ at the highest airflow, with an increase of approximately 60 mg/m³ relative to the optimum. This effect is due to enhanced oxygen availability, which promote NO_x formation [32-33]. Although this trend is consistent with the results of Ciupek et al. (2024), who reported that air gradation tends to increase NO_x levels even as CO and unburned hydrocarbons decrease, the absolute growth observed in the present study is moderate compared to the dramatic improvements in CO oxidation [31].

For comparison, Backa et al. (2025) reported that under similar fuel supply rates, but without the application of tertiary air, adjustments limited to the primary and secondary airflow from the main fan were insufficient to achieve comparably low CO emissions or equivalent thermal performance [25].

References

- [1] JOHANSSON, L. S., LECKNER, B., GUSTAVSSON, L., COOPER, D., TULLIN, C., POTTER, A. Emission characteristics of modern and old-type residential boilers fired with wood logs and wood pellets. *Atmospheric Environment* [online]. 2004, **38**(25), p. 4183-4195. ISSN 1352-2310, eISSN 1878-2442. Available from: <https://doi.org/10.1016/J.ATMOENV.2004.04.020>

4 Conclusion

Overall, the results indicate that a tertiary airflow of approximately 8.9 m³/h constitutes the optimal operating condition for the tested pellet boiler. At this setting, the system achieved the most homogeneous temperature distribution, the highest measured thermal output, and a drastic reduction in CO emissions, while the increase in NO_x remained moderate. It should be noted, however, that the optimal value of tertiary airflow is linked to the concurrent settings of the primary and secondary air supply, as well as to the fuel feed rate; adjustments in these parameters would necessitate a corresponding modification of the tertiary air delivery. Nevertheless, the results clearly demonstrate the beneficial impact of supplying air directly into the flame zone, leading to a substantial reduction of emissions. These findings align with the broader literature, which emphasizes that the staged air strategies, particularly the introduction of additional air directly into the flame zone, represent one of the most effective methods to enhance combustion completeness, improve boiler efficiency, and reduce harmful emissions in small-scale biomass boilers [34-35].

When the tertiary air was applied at approximately 9 m³/h, a slight improvement in efficiency (approximately 2%) was observed. More importantly, the CO emissions normalized to 10% O₂ decreased almost twentyfold compared to operation without the tertiary air at the same setting. On the other hand, NO_x emissions at 10% O₂ increased moderately by about 60 mg/m³.

Acknowledgements

This publication has been produced with the support of VEGA No. 1/0150/22: Energy utilization of produced waste in connection with the COVID-19 pandemic through pellets as an alternative fuel and VEGA No. 1/0311/26: Autonomous control of the combustion process in small heat sources using artificial intelligence.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

- [2] VAN LOO, S., KOPPEJAN, J. *The handbook of biomass combustion and cofiring*. London: Earthscan Publications Ltd., 2008. ISBN 978-1-84407-249-1.
- [3] KUBAS, J., BALLAY, M., RISTVEJ, J., ZABOVSKA, K. Empirical measurement of electromobility efficiency in the environment of the European Union. *Communications - Scientific Letters of the University of Zilina* [online]. 2022, **24**(3), p. A123-A132. ISSN 1335-4205, eISSN 2585-7878. Available from: <https://doi.org/10.26552/COM.C.2022.3.A123-A132>
- [4] ORMAN, L. J., MAJEWSKI, G., RADEK, N., PIETRASZEK, J. Analysis of thermal comfort in intelligent and traditional buildings. *Energies* [online]. 2022, **15**(18), 6522. eISSN 1996-1073. Available from: <https://doi.org/10.3390/en15186522>
- [5] LATOSINSKA, J., GAWDZIK, J., HONUS, S., ORMAN, L. J., RADEK, N. Waste for building material production as a method of reducing environmental load and energy recovery. *Frontiers in Energy Research* [online]. 2023, **11**, 1279337. eISSN 2296-598X. Available from: <https://doi.org/10.3389/fenrg.2023.1279337>
- [6] MAJEWSKI, G., ORMAN, L. J., TELEJKO, M., RADEK, N., PIETRASZEK, J., DUDEK, A. Assessment of thermal comfort in the intelligent buildings in view of providing high quality indoor environment. *Energies* [online]. 2020, **13**(8), 1973. eISSN 1996-1073. Available from: <https://doi.org/10.3390/en13081973>
- [7] RIMAR, M., KIZEK, J., KULIKOV, A., FEDAK, M. Study of selected burner parameters on the gas-air mixture combustion. *MM Science Journal* [online]. 2022, **2022**(5), p. 6251-6256. ISSN 1803-1269, eISSN 1803-0476. Available from: https://doi.org/10.17973/MMSJ.2022_12_2022158
- [8] PEDRETTI, F. E., TOSCANO, G., DUCA, D., PIZZI, A., RIVA, G. Effects of the quality of the biomass on combustion emissions of stoves and small boilers. In: International Conference Ragusa SHWA2010 - Work Safety and Risk Prevention in Agro-food and Forest Systems: proceedings. 2010. ISSN 2532-103X, p. 585-591.
- [9] BIGNAL, K. L., LANGRIDGE, S., ZHOU, J. L. Release of polycyclic aromatic hydrocarbons, carbon monoxide and particulate matter from biomass combustion in a wood-fired boiler under varying boiler conditions. *Atmospheric Environment* [online]. 2008, **42**(39), p. 8863-8871. ISSN 1352-2310, eISSN 1878-2442. Available from: <https://doi.org/10.1016/J.ATMOSENV.2008.09.013>
- [10] KLEMENT, I., VILKOVSKA, T., UHRIN, M., BARANSKI, J., KONOPKA, A. Impact of high temperature drying process on beech wood containing tension wood. *Open Engineering* [online]. 2019, **9**(1), p. 428-433. eISSN 2391-5439. Available from: <https://doi.org/10.1515/ENG-2019-0047>
- [11] HORAK, J., LACIOK, V., KRPEC, K., HOPAN, F., DEJ, M., KUBESA, P., RYSAVY, J., MOLCHANOV, O., KUBONOVA, L. Influence of the type and output of domestic hot-water boilers and wood moisture on the production of fine and ultrafine particulate matter. *Atmospheric Environment* [online]. 2020, **229**, 117437. eISSN 1352-2310. Available from: <https://doi.org/10.1016/J.ATMOSENV.2020.117437>
- [12] TRNKA, J., HOLUBCIK, M., CAJOVA KANTOVA, N., JANDACKA, J. Energy performance of a rotary burner using pellets prepared from various alternative biomass residues, *BioResources* [online]. 2021, **16**(4), p. 6737-6749. ISSN 1930-2126. Available from: <https://doi.org/10.15376/biores.16.4.6737-6749>
- [13] JANDACKA, J., HOLUBCIK, M., PAPUCIK, S., NOSEK, R. Combustion of pellets from wheat straw. *Acta Montanistica Slovaca*. 2012, **17**(4), p. 283-289. ISSN 1335-1788.
- [14] JANDACKA, J., NOSEK, R., HOLUBCIK, M. Effect of selected additives to properties of wood pellets and their production/Vplyv vybranych aditiv na vlastnosti drevnych peliet a na ich vyrobu (in Slovak). *Acta Facultatis Xylologiae Zvolen*. 2011, **53**(2), p. 85-91. ISSN 1336-3824.
- [15] HOLUBCIK, M., JANDACKA, J., PALACKA, M., KANTOVA, N., JACHNIAK, E., PAVLIK, P. The impact of bark content in wood pellets on emission production during combustion in small heat source. *Communications - Scientific Letters of the University of Zilina* [online]. 2017, **19**(2A), p. 94-100. ISSN 1335-4205, eISSN 2585-7878. Available from: <https://doi.org/10.26552/COM.C.2017.2A.94-100>
- [16] NUSSBAUMER, T., DOBERER, A., KLIPPEL, N., BUHLER, R., VOCK, W. Influence of ignition and operation type on particle emissions from residential wood combustion. In: 16th European Biomass Conference and Exhibition: proceedings. 2008.
- [17] FACHINGER, F., DREWNICK, F., GIERE, R., BORRMANN, S. How the user can influence particulate emissions from residential wood and pellet stoves: Emission factors for different fuels and burning conditions. *Atmospheric Environment* [online]. 2017, **158**, p. 216-226. eISSN 1352-2310. Available from: <https://doi.org/10.1016/J.ATMOSENV.2017.03.027>
- [18] HOLUBCIK, M., CAJOVA KANTOVA, N., JANDACKA, J., CAJA, A. The performance and emission parameters based on the redistribution of the amount of combustion air of the wood stove. *Processes* [online]. 2022, **10**(8), 1570. eISSN 2227-9717. Available from: <https://doi.org/10.3390/PR10081570>
- [19] KRAVCHENKO, O., BAZHYNOV, O., DIZO, J., HAIEK, Y., BLATNICKY, M. Cleaning dusty air flow with a rotary cyclone from dispersed particles. *Communications - Scientific Letters of the University of Zilina* [online]. 2025, **27**(1), p. B21-B29. ISSN 1335-4205, eISSN 2585-7878. Available from: <https://doi.org/10.26552/COM.C.2025.004>

- [20] REGUEIRO, A., PATINO, D., PORTEIRO, J., GRANADA, E., MIGUEZ, J. L. Effect of air staging ratios on the burning rate and emissions in an underfeed fixed-bed biomass combustor. *Energies* [online]. 2016, **9**(11), 940. eISSN 1996-1073. Available from: <https://doi.org/10.3390/EN9110940>
- [21] KHODAEI, H., GUZZOMI, F., PATINO, D., RASHIDIAN, B., YEOH, G. H. Air staging strategies in biomass combustion-gaseous and particulate emission reduction potentials. *Fuel Processing Technology* [online]. 2017, **157**, p. 29-41. eISSN 0378-3820. Available from: <https://doi.org/10.1016/J.FUPROC.2016.11.007>
- [22] CARROLL, J. P., FINNAN, J. M., BIEDERMANN, F., BRUNNER, T., OBERNBERGER, I. Air staging to reduce emissions from energy crop combustion in small scale applications. *Fuel* [online]. 2015, **155**, p. 37-43. ISSN 0016-2361, eISSN 1873-7153. Available from: <https://doi.org/10.1016/J.FUEL.2015.04.008>
- [23] SHEN, G., XUE, M., WEI, S., CHEN, Y., ZHAO, Q., LI, B., WU, H., TAO, S. Influence of fuel moisture, charge size, feeding rate and air ventilation conditions on the emissions of PM, OC, EC, parent PAHs, and their derivatives from residential wood combustion. *Journal of Environmental Sciences* [online]. 2013, **25**(9), p. 1808-1816. ISSN 1001-0742, eISSN 1878-7320. Available from: [https://doi.org/10.1016/S1001-0742\(12\)60258-7](https://doi.org/10.1016/S1001-0742(12)60258-7)
- [24] BACKA, A., NOSEK, R., CAJOVA KANTOVA, N., SLADEK, S. Spatial distribution of emissions, temperatures, and particulate matter in a combustion zone of a pellet boiler. *Case Studies in Thermal Engineering* [online]. 2025; **73**, 106631. eISSN 2214-157X. Available from: <https://doi.org/10.1016/J.CSITE.2025.106631>
- [25] BACKA, A., CAJOVA KANTOVA, N., NOSEK, R., PATSCH, M. Evaluating the combustion of various biomass pellets in a small heat source with underfeed pellet burner: heat output, gas emission and ash melting behavior. *Journal of the Energy Institute* [online]. 2025, **118**, 101936. ISSN 1743-9671, eISSN 1746-0220. Available from: <https://doi.org/10.1016/J.JOEI.2024.101936>
- [26] FLACH, B., BOLLA, S. Wood pellets annual. Washington, DC: USA: U.S. Department of Agriculture, 2024.
- [27] STN EN 16510-1. Residential solid fuel burning appliances - part 1: general requirements and test methods. 2023.
- [28] Commission Regulation (EU) 2015/1189 of 28 April 2015 implementing Directive 2009/125/EC of the European Parliament and of the Council with regard to ecodesign requirements for solid fuel boilers. 2015.
- [29] ZANDECKIS, A., KIRSANOV, V., DZIKEVICS, M., BLUMBERGA, D. Experimental study on the optimisation of staged air supply in the retort pellet burner. *Agronomy Research*. 2013, **11**(2), p. 381-390. ISSN 1406-894X.
- [30] KARDAS, D., WANTULA, M., PIETER, S., KAZIMIERSKI, P. Effect of separating air into primary and secondary in an integrated burner housing on biomass combustion. *Energies* [online]. 2024, **17**(18), 4648. eISSN 1996-1073. Available from: <https://doi.org/10.3390/EN17184648>
- [31] 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* [online]. 2024, **17**(13), 3087. eISSN 1996-1073. Available from: <https://doi.org/10.3390/EN17133087>
- [32] LUKAC, L., KIZEK, J., JABLONSKY, G., KARAKASH, Y. Defining the mathematical dependencies of NO_x and CO emission generation after biomass combustion in low-power boiler. *Civil and Environmental Engineering Reports* [online]. 2019, **29**(3), p. 153-163. ISSN 2080-5187, eISSN 2450-8594. Available from: <https://doi.org/10.2478/ceer-2019-0031>
- [33] LUKAC, L., RIMAR, M., VARINY, M., KIZEK, J., LUKAC, P., JABLONSKY, G., JANOSOVSKY, J., FEDAK, M. Experimental investigation of primary de-NO_x methods application effects on NO_x and CO emissions from a small-scale furnace. *Processes* [online]. 2020, **8**(8), 940. eISSN 2227-9717. Available from: <https://doi.org/10.3390/pr8080940>
- [34] WANG, Z., YANG, X. NO_x Formation mechanism and emission prediction in turbulent combustion: a review. *Applied Sciences* [online]. 2024, **14**(14), 6104. eISSN 2076-3417. Available from: <https://doi.org/10.3390/APP14146104>
- [35] BELOHRADSKY, P., SKRYJA, P., HUDAK, P. Experimental study of oxygen-enhanced combustion on NO_x emission, in-flame temperatures and heat flux distribution. *Chemical Engineering Transactions* [online]. 2014, **39**, p. 787-792. ISBN 978-88-95608-30-3, ISSN 2283-9216. Available from: <https://doi.org/10.3303/CET1439132>