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The Performance and Emission Parameters Based on the Redistribution of the Amount of Combustion Air of the Wood Stove

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Abstract: Several factors affect how particulate matter and gaseous emissions are formed during the combustion processes of biomass. The amount of combustion air, as well as its redistribution, is one of these factors. This article deals with the performance and emission parameters determined using different distributions of the amount of combustion air of the wood stove with beech wood as a fuel. Eighteen different settings of primary, secondary and tertiary air supplies were realized, while heat output, efficiency, particulate matter, carbon monoxide and nitrogen oxides were measured or determined. The aim of this article is to identify the optimal air distribution between primary, secondary, and tertiary air supplies focused on the mentioned parameters. Based on the results, two settings (25/50/25 and 0/100/0) could be the optimal variant. However, the concentration of particulate matter reached a higher value during the setting with a ratio of 25/50/25, similar to a ratio of 50/25/25. The measurement during the setting with a ratio of 0/100/0 could be influenced by the existing embers on the grid before the start of the measurement. However, it is important to supply all three types of combustion air with the main emphasis on the secondary air supply due to the completely use of the combustible gases.

Keywords: particulate matter; emissions; combustion; burning condition; air distribution; air supply

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1. Introduction

Biomass is the only renewable carbon-based fuel. Among the other thermochemical processing technologies, fuel combustion is one of the most reliable methods for producing heat and electricity [1]. For this reason, the use of solid biofuels has been the fastest-growing source of energy in the last two decades. In many cases, people still use equipment designed for combustion of coal or other fuels. As a result, the combustion process is not sufficiently controlled and incomplete combustion occurs. Stoves designed specifically for biomass fuels are gradually being introduced. A combustion device designed in this way can make better use of the energy contained in the fuel and thereby reduce emissions [2].

However, several factors affect the biomass combustion process. Vitázek et al. [3] state that the amount of gaseous emissions depends mainly on the fuel's quantity and uniformity, the relative humidity, and the fuel type, and also on keeping to the fuel mix recommended by the boiler's manufacturer. Nussbaumer et al. [4] investigated the influence of different phases of the entire combustion cycle on the formation of particulate matter (PM). The measurement was performed on a manually operated wood-burning stove. The burn-in took approximately 6 h and the start-up phase approximately 20 min. During the first 20 min (approximately 7% of the combustion cycle), approximately 50% of total PM emissions were released. Thus, the start-up phase had a strong influence on PM formation. Fachinger et al. [5] observed the effect of combustion velocity on the production of emissions in fireplace stoves. Velocities that were very high or very low led to an increase in emission factor values. Nussbaumer et al. [4] investigated the effect of different fuel ignition methods on the formation of PM particles. Ignition from the top had a more favorable effect and led to a more gradual and complete burnout of the fuel. This type of ignition was also able to reduce the production of particulate matter by 50% to 80% compared to traditional ignition from the bottom. The effect of settings of different chimney drafts was also observed in this study. A higher amount of PM formation was mainly found during the ignition phase.

Polonini et al. [6] observed the amounts of generated emissions of PM and carbon monoxide (CO) depending on the different layouts of air inlets. The measurements were performed on stoves that burn pellets with a newly developed burner pot and those with a traditional burner pot. The innovative burner was designed for the supply of primary, secondary, and also tertiary combustion air. The geometry was designed in such a way that almost ideal combustion is achieved during combustion. According to tests, the new burner pot can greatly reduce CO emissions while also significantly reducing PM, but not as significantly as CO emissions. However, it appeared that the amount of PM released was dependent on how long it took for the stoves B1 (8.6 kW) and B2 (10.1 kW) to ignite. PM emissions tended to increase over time.

The impact of fuel moisture was recorded in several works. For example, Bignal et al. [7] reported that CO and polycyclic aromatic hydrocarbon (PAH) emission factors for high moisture fuel were about 2 to 5 times higher than for low moisture fuel. The results of Pedretti et al. [8] indicate that with an increase in moisture from 25 to 45%, there was a two-fold increase in the concentration of PM particles in wood chips burned in a boiler. Horák et al. [9] investigated the influence of the type and output of boilers and also moisture on PM production. There was a very significant decrease in the PM concentration in the new boilers, but the amount of ultrafine particles was in a similar range. The PM production was higher during the combustion of wet spruce wood. However, the high temperature drying of wood has a significant impact on its dimensional and selected physical changes, according to Klement et al. [10].

Different fuels have different chemical properties, which causes differences in the combustion process and also the production of emissions. The most important properties of fuels that affect combustion can be the type of biomass (dendromass, phytomass), the place of cultivation, and the form in which the investigated fuel is burned (chips, briquettes, pellets, wood pieces, etc.) as well as the age of the fuel [11]. Nosek et al. [12] investigated the impact of the temperature of combustion air. The measurement was performed on a 6 kW fireplace stove with primary and secondary air supply, where beech wood was used as fuel. The PM measurement reached the maximum value at 30 °C and a PM concentration of 200 $mg \cdot m^{-3}$. The minimum values were reached at 35 °C with a PM concentration of 60 $mg \cdot m^{-3}$. The stated results indicate that the influence of the change in temperature of the primary combustion air was not significant. Holubčík et al. [13] also investigated the influence of the geometric parameters of the fuel on the combustion process. The results showed that the highest heat output and efficiency and the lowest emissions were recorded during combustion of one piece of wood or, respectively, two pieces compared to three and four pieces.

To achieve higher efficiency and lower emissions, it is necessary to ensure the supply of the necessary amount of air in the correct ratio to the combustion chamber. The air can be even supplied by three different inlets: primary, secondary, and tertiary. The primary air may be supplied under the grate. This supply is important mainly in the phase of drying and heating the fuel. If the combustion is to be more perfect, it is also necessary to supply the secondary air. Secondary air may be supplied to the combustion device above the grate. Its task is to ensure that the generated combustible gases are completely used [1]. Tertiary air may be mainly used for larger and more powerful boilers. It may be used for airflow on a glass of wood stoves and prevents the leakage of unburned gases during secondary combustion and carbon monoxide [14]. Regueiro et al. [15] investigated the influence of the operating parameters of the combustion process at low air redistribution ratios (15–30%).

The concentration of PM in these cases ranged from 15 to 75 mg·N^{-1}·m^{-3} at 6% O_2 in the worst case. However, it was confirmed that when only primary air is used without redistribution, the particle concentration has a value higher than 360 mg·N^{-1}·m^{-3} at 6% O_2. As the primary air flow increased, nitrogen oxides (NO_X) and CO emissions also went up. Shen et al. [16] conducted measurements of air ventilation and burning rate depending on emission factors. The majority of pollutants were lowest during normal burning under conditions of sufficient air supply, but more pollutants were released during fast burning when an oxygen-deficient atmosphere was created in the stove chamber.

Air redistribution is one thus of several factors which may impact the biomass combustion process. This article deals with the redistribution of the amount of combustion air of the wood stove into primary, secondary and tertiary air supplies, while the performance (heat output and efficiency) and emission (PM, CO and NO_X) parameters were observed. The main aim is to identify the optimal air redistribution focused on the mentioned parameters.

2. Materials and Methods

2.1. Used Fuel

Pieced beech wood was used as fuel for heating. During the entire measurement, the same fuel with a weight of approximately 1.3 ± 0.2 kg was used. The value was chosen based on the calculation in Equation (1) according to the STN EN 16510-1 [17].

$$B_{fl} = \frac{360\,000 \cdot P_n \cdot \tau_b}{H_u \cdot \eta} \tag{1}$$

In Equation (1) B_{fl} is weight of delivered fuel [kg], H_u is lower calorific value of test fuel [kJ·kg^{-1}], η—the smallest efficiency determined by the standard or the manufacturer [%], P_n—nominal heat output [kW] and τ_b—shortest fuel supply interval [hours].

Table 1 shows the proximate and ultimate analyses of used beech wood.

Table 1. The proximate and ultimate analyses of beech wood.

Fuel	C^{daf} [%]	H^{daf} [%]	N^{daf} [%]	O^{daf} [%]	A^r [%]	W^r [%]
Beech wood [18]	49.13	6.11	0.15	44.17	0.57	0

2.2. The Amount and Velocity of Combustion Air

The amount of standardized combustion air under normal operating conditions V^S_{vzn} was calculated from the chemical composition of the used fuel and based on Equation (2). Beech wood has been used as a fuel for combustion. The necessary proximate and ultimate analyses are stated in Table 1.

$$V^S_{vzn} = \frac{\lambda_{opt}}{0.21}\left[1867\frac{C^{daf}}{100} + 5.6\frac{H^{daf}}{100} + 0.8\frac{N^{daf}}{100} - 0.7\frac{O^{daf}}{100}\right] \cdot \left[\frac{100 - A^r - W^r}{100}\right] \tag{2}$$

In Equation (2) C^{daf}, H^{daf} and N^{daf} constitute the content of the respective elements in the combustion fuel (kg·kg^{-1}), A^r is the ash content in the fuel (kg·kg^{-1}), W^r is the moisture content in the fuel (kg·kg^{-1}) and λ_{opt} is the optimal excess of combustion air with the considered value of 2.1. In general, the excess of combustion air for wood stoves is in the range from 1.7 to 2.5. Afterwards, the calculation of the real amount of combustion air was realized based on Equation (2) and the temperature and pressure of the air supply, and also fuel weight.

The calculation of the redistribution of amount of the combustion air between the primary, secondary and tertiary supply was carried out through Equations (3) and (4).

$$Q_{prim} = \frac{A_{PS} \cdot V_{vzm}}{100 \cdot \tau_b} \tag{3}$$

$$v_{prim} = \frac{Q_{prim}}{3600 \cdot S_{sp}} \quad (4)$$

In Equations (3) and (4), Q_{prim} ($m^3 \cdot h^{-1}$) is air flow for primary supply, A_{PS} (%) is percentage content of primary supply from all supply, V_{vzm} [m^3] is real amount of combustion air, τ_b (hours) is fuel burning time, v_{prim} ($m \cdot s^{-1}$) is velocity of primary air supply and S_{sp} (m^2) is the surface of the pipe of combustion air supply. The secondary and tertiary air supply flow rates and velocities were obtained in a similar way. Table 2 shows all calculated values of air supply velocities for eighteen different settings of air velocity redistribution ratios. These velocities were set up during combustion measurements by fan velocity settings and also opening or closing of the regulating measuring aperture.

Table 2. The resulting calculated air supply velocities.

The Ratio of Air Velocity Redistribution (%)			The Velocity of Air Redistribution ($m.s^{-1}$)		
Primary	**Secondary**	**Tertiary**	**Primary**	**Secondary**	**Tertiary**
0	0	100	0	0	1.13
0	25	75	0	0.28	0.83
0	50	50	0	0.56	0.56
0	75	25	0	0.83	0.28
0	100	0	0	1.19	0
25	75	0	0.26	0.79	0
25	50	25	0.28	0.56	0.28
25	25	50	0.29	0.29	0.58
25	0	75	0.28	0	0.84
50	0	50	0.55	0	0.55
50	25	25	0.56	0.28	0.28
50	50	0	0.45	0.45	0
75	0	25	0.75	0	0.25
75	25	0	0.81	0.27	0
65	25	10	0.59	0.23	0.09
70	25	5	0.66	0.24	0.05
80	20	0	0.73	0.18	0
100	0	0	1.06	0	0

2.3. The Experimental Setup

Figure 1 presents the experimental setup with a wood stove, into which combustion air was supplied through three inlets. The distribution of the individual types of air supply is shown in more detail in Figure 2. The used stove had an underfeed fixed bed and its nominal heat output was 6 kW.

The air velocity was measured using an anemometer FVAD 15—HMK5 with a measuring range of 0.15 $m \cdot s^{-1}$ to 5 $m \cdot s^{-1}$ and operative range of −20 °C to +125 °C. The accuracy of the used anemometer was ±0.5% of the final value sensor and ±1.0% of the measured value. The measurement equipment for PM and gas emissions is a part of Figure 1.

Gaseous emissions were sampled using an ABB AO 2020 flue gas analyzer with sensor modules Uras 26 (NDIR photometer for continuous CO_2, CO, NO_X measuring) with accuracy ≤1% of span and oxygen analyser module Magnos 206 (paramagnetic behaviour of oxygen) with accuracy ±0.5%.

Particulate matter was sampled using a gravimetric probe located in the flue pipe. The Tecora ISOSTACK BASIC evaluation device was connected to the gravimetric probe along with other components such as a Pitot tube, a cooling box, and a silica gel dryer. Gravimetric method is given by the standard STN ISO 9096 [19]. It is a manual, single-use method where samples are taken by a probe from flowing gas. This method gives an average value of PM for a given span of time within which a partial flow from an exhaust gas sample is taken. Exhaust gases are guided through filtration or sediment systems which catch either all particles or only those of pre-defined size. Filtration materials are weighed before and after measurements and final mass concentration is calculated from a sample volume. Sampling probes can be placed either directly into hot flow of exhaust gases or outside the flow (these systems must be heated to avoid condensation or nucleation). The accuracy of this method influences various parameters, mainly differential pressure in Pitot tube ±4 Pa, temperature of flue gas ±0.7% K, flow rate and volume measure ±2% and filter weight ± 0.1 mg. The sampling was isokinetic and the isokinetic deviation during all experiments was in the range −4.5 ÷ 3.8%.

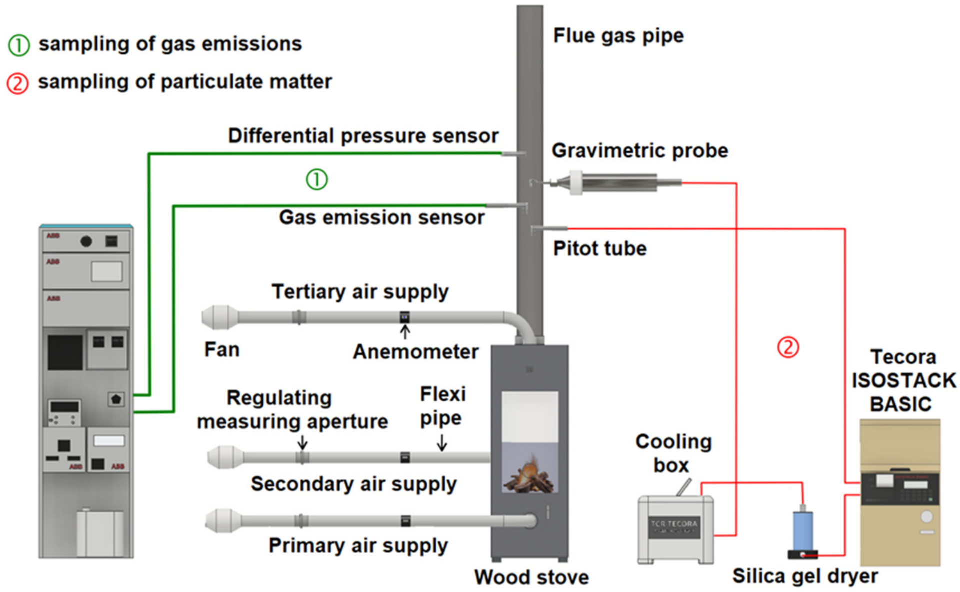

Figure 1. The experimental setup.

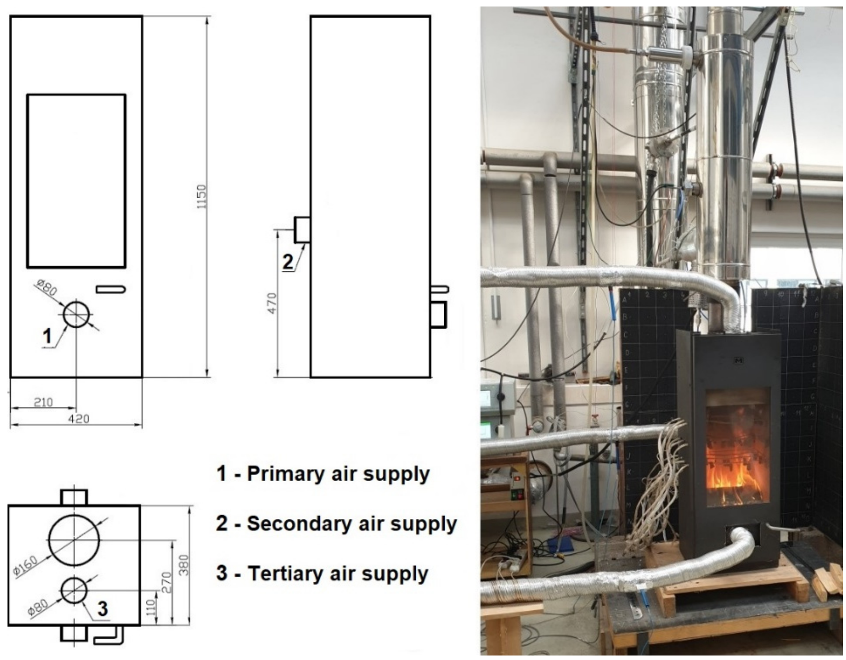

Figure 2. The distribution of the individual air supplies.

Figure 2 presents the distribution of the primary, secondary and tertiary air supply. Primary air was supplied to the lower part of the wood stove under the grate by a fan through a Flexi pipe. The supply of secondary combustion air was provided from the back of the stove above the grate also transported by a fan through a Flexi pipe. The tertiary combustion air was supplied the same way as primary and secondary inlets but placed in the upper part of the stove for airflow on the glass.

2.4. The Performance and Emission Parameters

The efficiency η calculation consists of individual heat losses according to the STN EN 16510-1 [17], thermal heat losses in the flue gas q_a (%), chemical heat losses in the flue gas q_b [%] and heat losses in residue q_r (%), as shown in Equation (5). Chimney temperature for determining q_a was measured by resistance thermometer pt100 1/5 DIN class B with accuracy ±0.05 K ±0.05% of measured value and heat losses in residue q_r were taken as 0.5% according to the STN EN 16510-1 [17].

$$\eta = 100 - (q_a + q_b + q_r) \tag{5}$$

The heat output P (kW) was calculated from the weight of the fuel burned per hour B (kg·h^{-1}), from the lower calorific value of the fuel H_u (kJ·kg^{-1}), and from the efficiency η (%) according to Equation (6).

$$P = \frac{H_u \cdot B \cdot \eta}{100} \tag{6}$$

The measured values of gaseous emissions were in units of ppm. The conversion to units of mg·m^{-3} and at the same time to the 13% of O_2 in the flue gas according to the STN STN EN 16510-1 [17] standard is given in Equation (7).

$$CO_{13\%} = CO_{ppm} \cdot d_{CO} \cdot \frac{21-13}{21-O_2} \tag{7}$$

In Equation (6), $CO_{13\%}$ is the standard value of CO for 13% of O_2, CO_{ppm} is the measured value of CO in the value of ppm, d_{CO} (kg·m^{-3}) is the density of CO and O_2 is the measured value of O_2 (%). NO_X standard values were determined in the same way.

The calculation of PM concentration was carried out according to Equation (8), where C (mg·m^{-3}) is PM concentration in dry gas, m_1 (mg) is the filter weight before measurement, m_2 (mg) is the filter weight after measurement and V_{gn} (m^3) is the sample volume.

$$C = \frac{m_2 - m_1}{V_{gn}} \tag{8}$$

The conversion to PM concentration under reference conditions C^r (mg·m^{-3}) is shown in Equation (9), where O_{2ref} (%) is the reference content of oxygen and O_{2oper} (%) is oxygen content for operating conditions during measurement.

$$C^r = \frac{20.95 - O_{2\,ref}}{20.95 - O_{2\,oper}} \cdot C \tag{9}$$

Various parameters were recorded every 20 s. During the measurements, constant chimney draft 12 ± 2 Pa via a flue fan was ensured. Its velocity was controlled by a frequency regulator. The chimney draft was measured by differential pressure sensor with range 0–100 Pa with accuracy 0.5% of measured value of chimney draft.

The measurements were realized in three repetitions. The results are average values from the three types of measurements. The standard deviations were detected in the Excel program.

3. Results and Discussion

The comparison of the achieved efficiencies of the wood stove with different settings for the supply of combustion air is shown in Figure 3. The lowest efficiency with an average value of 47.8% was achieved with an air supply setting with a ratio of 75/0/25. The highest efficiency with an average value of 69.2% was achieved with an air supply setting with a ratio of 25/50/25. The calculated average value of standard deviation was ±1.8% for efficiency.

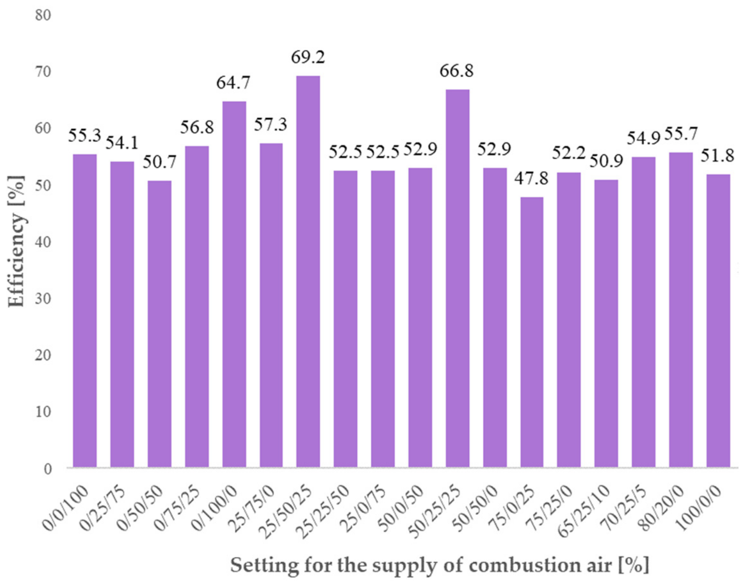

Figure 3. The efficiency comparison during different settings for air supply.

The comparison of the achieved heat outputs of the wood stove with different settings for the supply of combustion air is shown in Figure 4. The lowest heat output with an average value of 3.1 kW was achieved with an air supply setting with a ratio of 65/25/10. The highest heat output with an average value of 5.1 kW was achieved with an air supply setting with a ratio of 0/100/0 and also 25/50/25. The calculated average value of standard deviation was ±0.15 kW for heat output.

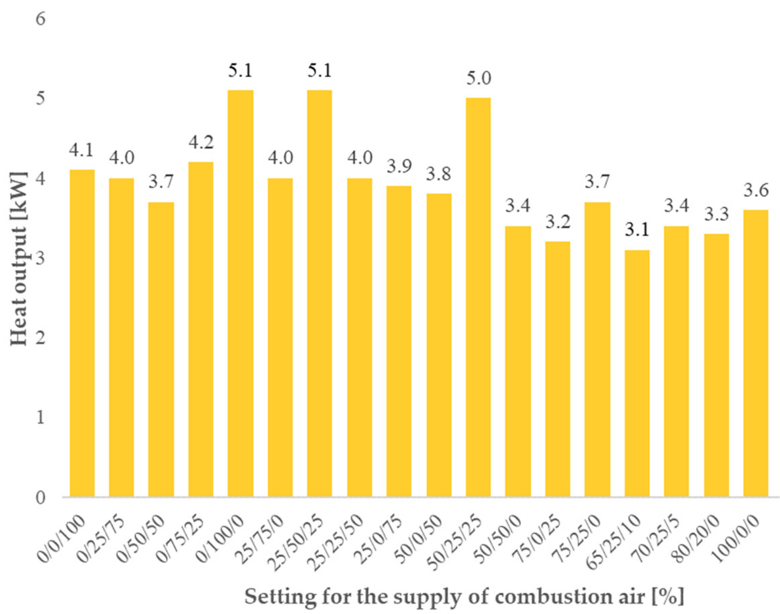

Figure 4. The heat output comparison during different settings for air supply.

The comparison of the detected carbon monoxide during combustion in the wood stove with different settings for the supply of combustion air is shown in Figure 5. The lowest $CO_{13\%}$ with an average value of 1115.3 mg·m^{-3} was achieved with an air supply setting with a ratio of 25/50/25. The highest $CO_{13\%}$ with an average value of 4196.2 mg·m^{-3} was achieved with an air supply setting with a ratio of 80/20/0. The calculated average value of standard deviation was ±322 mg·m^{-3} for carbon monoxide.

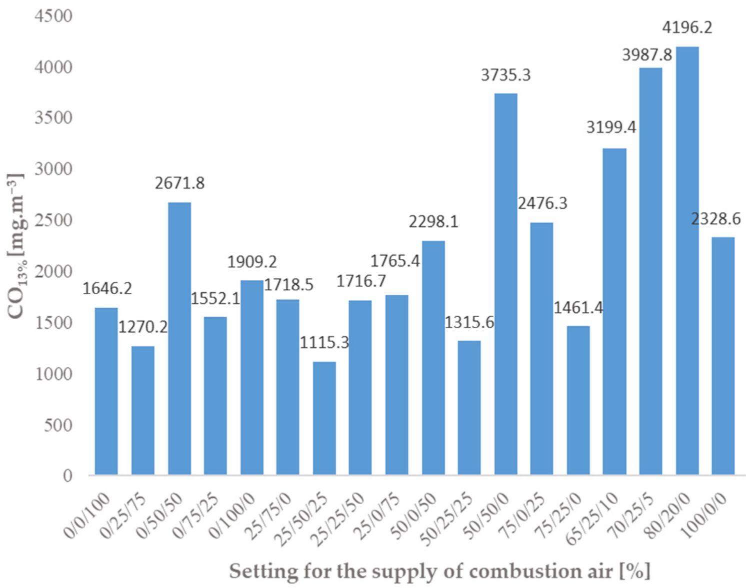

Figure 5. The carbon monoxide formation during different settings for air supply.

The comparison of the detected nitrogen oxides during combustion in the wood stove with different settings for the supply of combustion air is shown in Figure 6. The lowest $NO_{X13\%}$ with an average value of 88.7 mg·m^{-3} was achieved with an air supply setting with a ratio of 25/50/25. The highest $NO_{X13\%}$ with an average value of 145.3 mg·m^{-3} was achieved with an air supply setting with a ratio of 80/20/0. The calculated average value of standard deviation was ±15 mg·m^{-3} for nitrogen oxides.

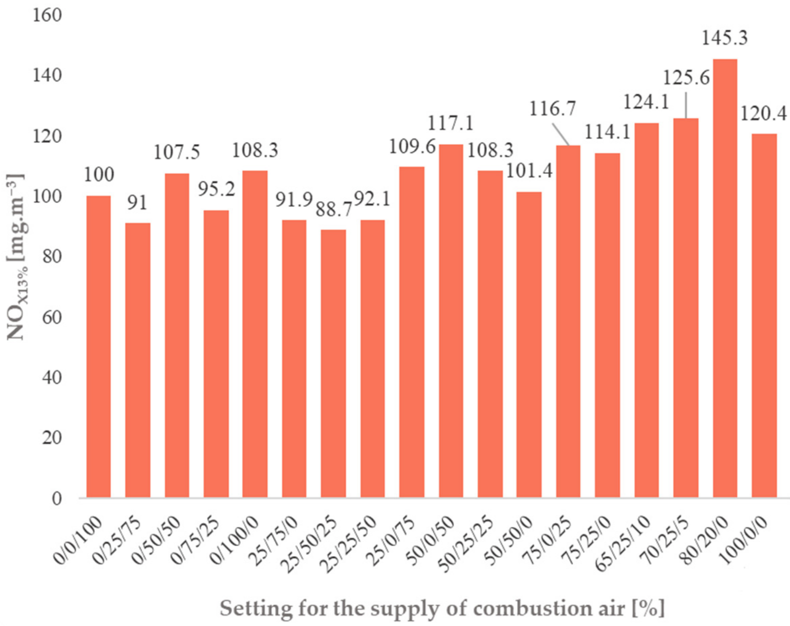

Figure 6. The formation of nitrogen oxides during different settings for air supply.

The comparison of the detected particulate matter during combustion in the wood stove with different settings for the supply of combustion air is shown in Figure 7. The lowest PM concentration with an average value of 59.98 mg·m^{-3} was achieved with an air supply setting with a ratio of 50/50/0. The highest PM concentration with an average value of 174.09 mg·m^{-3} was achieved with an air supply setting with a ratio of 25/75/0.

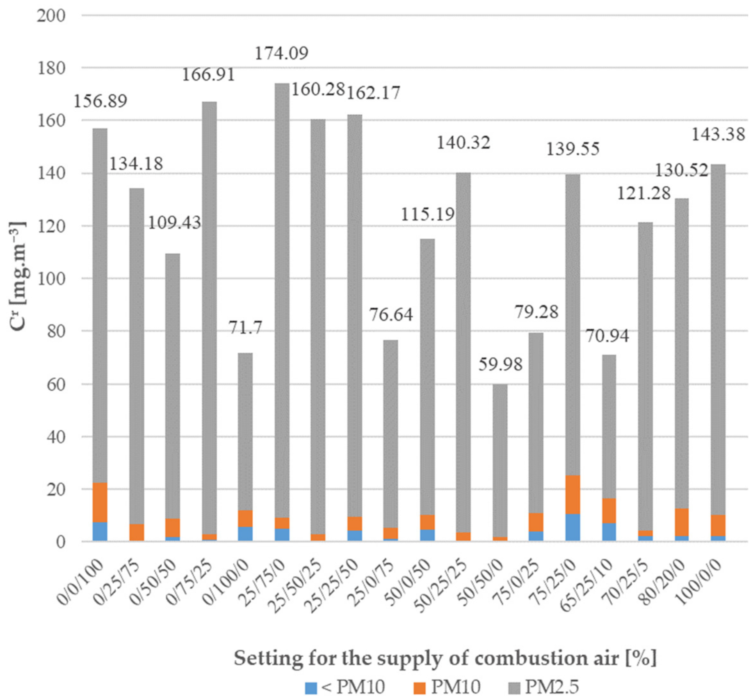

Figure 7. The formation of particulate matter during different settings for air supply.

The calculated average value of standard deviation was ±26 mg·m^{-3} for particulate matter. This value is higher, caused probably by automatic regulation of the flow based on the velocity of the flue gases necessary for isokinetic condition, then by change of pressure ratios on the chimney and in the space (for example caused by open windows) and by a slow reaction of the flow rate to velocity changes.

However, measuring errors may have occurred, such as the decline in chimney temperature or chimney draft, or other errors caused by manipulating the gravimetric probe in the flue pipe or by adding fuel to the wood stove.

Kshirsagar and Kalamkar [20] found that optimum values for CO emission were during an air ratio primary/secondary = 1.9 for biomass cookstoves. However, no optimum for $PM_{2.5}$ emissions were specified. The combustion was realized with primary air by natural draft and preheated secondary air by forced draft. Zhou et al. [21] suggested a ratio of primary to secondary air 43:57 with excess air ratio of 1.5 for the industrial-scale grate boiler. This was investigated through numerical simulation and validated with experimental measurements. Their results also suggested that higher air supply leads to early fuel combustion and adversely impacts the total efficiency. Higher primary air flow also has an enhanced cooling effect, which is helpful to ash cooling but unfavorable to initial fuel heating and drying. Deng et al. [22] investigated a forced-draft biomass pellet stove and concluded that burning and emission performances were better with a similar proportion of primary and secondary air supply, namely from 4:6 to 6:4 and with a total airflow rate of 184 L·min^{-1}. They tested six distributions between primary and secondary air supply during three different total airflow rates. On the contrary, Sun et al. [23] stated that a higher primary air supply led to lower particulate matter. Tryner et al. [24] observed minimum CO emissions for air ratios primary to secondary 3:1 and 4:1. Based on this experience, it is difficult to know the optimum ratio for air supplies considering the desired power and emission values.

Despite a higher PM concentration, the optimal variant of the setting of air supplies in this work could be with a set of air ratios of 25/50/25 with respect to performance and emission parameters. The ratio of 0/100/0 also appears to be a suitable variant in this article, but this measurement could be influenced by the existing embers on the grid before the start of the measurement. Favorable results were achieved during a set of air ratios of 50/25/25, but with a higher concentration of particulate matter also.

4. Conclusions

The formation of particulate matter and gaseous emissions during biomass combustion is influenced by many aspects. One of these aspects is how much combustion air needs to be supplied to the heat source during combustion and how to redistribute it. In addition to the emission production, the heat output and efficiency of the heat source were also determined in this article. The measurement with the lowest values of PM concentration was achieved when the air supply was set to a ratio of 50/50/0. The values of the concentration of gas emissions together with heat output and efficiency reached average levels, but not exactly low levels during this setting. Based on the analysis of gaseous emissions (CO and NO_X), the measurement using the setting of a ratio of 25/50/25 could be the best in terms of achieving suitable efficiency and heat power. However, the PM concentration using this setting reached a higher value.

The highest PM concentration was found when the air supply ratio was set to 0/75/25, which could be due to the lack of primary air, which needs to be supplied mainly in the start-up phase. The highest concentration of CO and NO_X was found at the setting of a ratio of 80/20/0, which may have been due to the high amount of primary air, which could result in incomplete combustion of the volatiles.

The optimal variant of the setting of air supplies in this work could be with a set of air ratios of 25/50/25 but with a higher PM concentration. The ratio of 0/100/0 also could be a suitable variant, but this measurement could have been influenced by the existing embers on the grid before the start of the measurement. Favorable results were achieved during a set of air ratios of 50/25/25, but with a higher concentration of particulate matter also.

However, it is important to supply all three types of combustion air with the main emphasis on the secondary air supply to promote the complete use of combustible gases.

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