Gradual combustion of wood logs by the use of preheated air

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The tendency to automate operation and minimize human involvement in small-scale biomass boilers has led to an increase in pellet usage. Standardized biomass-derived solid fuels are getting a bigger share in the market. In this battle, traditional firewood is not yet ready to give in. Compared with the standardized fuels, the processing of firewood is cheaper, emits smaller amounts of parasite emissions whereas complete combustion and automation require further development. To achieve these requirements, wood log gasification is a promising intermediate step. The paper aims to design gasification and combustion chambers for a 25-kW wood-log-fired water boiler. For both processes, preheated air is used. Its appropriate distribution and preheating are the main tasks that are realized by the use of a CFD model. In the gasification chamber, the oxidation should take place at least 20 cm before the introduction of the secondary (combustion) air, which is introduced by the use of many openings. Their numbers and positions are envisaged to achieve as complete as possible combustion in a larger area and to divert the flame. A gradual introduction of air in a larger area should reduce carbon monoxide (CO), nitrogen oxides (NOx), and the emissions of volatile organic compounds (VOC), whereas the diversion of the flame should reduce the emissions of particulate matter.

Keywords: Combustion, Small-scale biomass boiler, CFD, Gasification, Air distribution

1. INTRODUCTION

To achieve sustainable development, mankind envisaged the need for energy systems to be renewable and sustainable, efficient and cost-effective, convenient and safe [1]. To meet these requirements, biomass is seen as one of the most promising energy sources. Moreover, the use of biomass as fuel leads to the mitigation of greenhouse gas emissions [2].

Biomass is the first fuel, which has been used for millenniums. More than half of all biomass is nowadays used as a fuel for household heating and cooking. In developing countries, that usage leads to a major cause of serious indoor pollution, particularly to women, small children, and the elderly [3]. Biomass is renewable organic material that comes from plants (including algae, trees, and crops) and animals in which the energy of sunlight is stored in chemical bonds [4,5]. The use of biomass reduces the need for fossil fuels, such as coal, oil, and natural gas, which have taken millions of years to evolve.

In small-scale biomass boilers, except for pellets and briquettes and in rare situations wood chips, firewood is still the dominant biomass fuel for traditional use. Although firewood is an ecological fuel and a renewable energy source, its combustion emits large amounts of pollutants into the atmosphere. The importance and the impact of these emissions are best illustrated by the increased concentrations of pollutants in urban and suburban areas with a large number of individual boilers, stoves, and furnaces in many cities in the Republic of Serbia. This problem is particularly accentuated during winter weather inversion. Solid biomass boilers emit numerous pollutants, of which the most attention is paid to carbon monoxide (CO), nitrogen oxides (NO_X), and volatile organic compounds (VOC). In the Republic of Serbia, wood biomass is currently used annually with 1.021 Mtoe, while its annual untapped potential is 0.509 Mtoe [6].

2. AN OVERVIEW OF THE FIREBOX DESIGN IN SMALL-SCALE BIOMASS BOILERS

Manufacturers of wood biomass stoves and boilers are making significant efforts to increase efficiency and reduce pollutant emissions. Compared with derived fuels such as wood pellets, briquettes, and chips, firewood is the most economically acceptable fuel. Except for the price, the advantage of firewood is lower emissions of indirect pollutants due to shorter transport and less need for processing during production. Oppositely, the main disadvantages of firewood are: difficult control of the combustion process and higher pollutant emissions into the atmosphere. To reduce emissions, wood is burned in multi-stages or boilers and stoves are paired with heat accumulators to establish a stationary combustion regime [7,8].

When it comes to multi-stage combustion, in the first stage the wood is incompletely burned (gasified), while in the second stage the combustible gas is burned. Gasification and combustion zones are physically separated in gasification boilers. The basic schemes of the most commonly used constructions are shown in Figure 1. Only DC (direct current) gasification of wood (air and combustible gas flow in the same direction) was applied to them, and in all shown designs the gasification chamber (which is also a fuel bunker) is usually above the combustion chamber of the combustible gas (boiler firebox). In addition to the shown designs, there are designs with transverse and opposite gasification [9], as well as in the case of a fixed bed gasification reactor. The presented constructions dominate the market due to reliability, elaborated principle (manufacturers most easily accept successfully elaborated principles), the possibility of burning wood with larger moisture content, and stable air and gas flow through the gasification zone. The construction shown in Figure 1.A is technically the simplest, but also the most environmentally unacceptable. Its deficiency is caused by the flue gas loaded with a large

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concentration of particulates. These particles fall to the bottom of the firebox, cool very quickly, and cause higher emissions of carbon monoxide (CO), a higher amount of unburned carbon in the ash, and a higher amount of particles in the flue gas. This problem is more pronounced when reducing the amount of fuel in the gasification chamber (position 1 in Figure 1) because then the resistance of air and gas flow decreases. Therefore, most of the firebox space is covered with refractory ceramics as in the design shown in Figure 1.B, which is found in references [10,11,12].

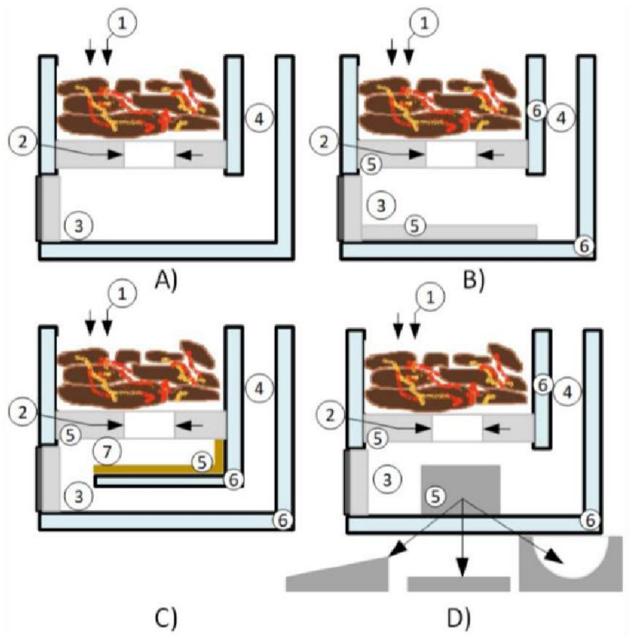

Figure 1: Analyzed designs of gasification boilers with direct current gasification of firewood. 1 – primary air (for gasification) and gasification chamber, 2 – secondary air (for combustion of combustible gas), 3 – combustion chamber, 4 – convective part of the boiler, 5 – refractory ceramic elements, 6 – water flow channels, 7 – intermediate chamber [13]

The design shown in Figure 1.C is often applied as can be seen in the reference [14]. This is a reliable design with some shortcomings. In the gasification chamber (position 1 in Figure 1), the airflow in one direction and burns incompletely the firewood. After leaving the gasification zone, the gas burns in the intermediate chamber (position 7 in Figure 1). The gasification zone and the intermediate chamber are divided by a plate of refractory ceramics (position 5 in Figure 1), whose role is to: limit the gasification zone and the firebox, keep the fuel being burned, enable the introduction and preheating of secondary air, and provide adequate mixing of producer gas from the gasification zone and combustion air. Figure 1.D shows the principle of design with a refractory insert. This type of design is found in references [15,16].

To achieve complete burnout and high efficiencies in small-scale combustion, downdraft boilers with the inverse flow have been introduced, which apply the two-stage combustion principle which is found in reference [17] and shown in Figure 2.

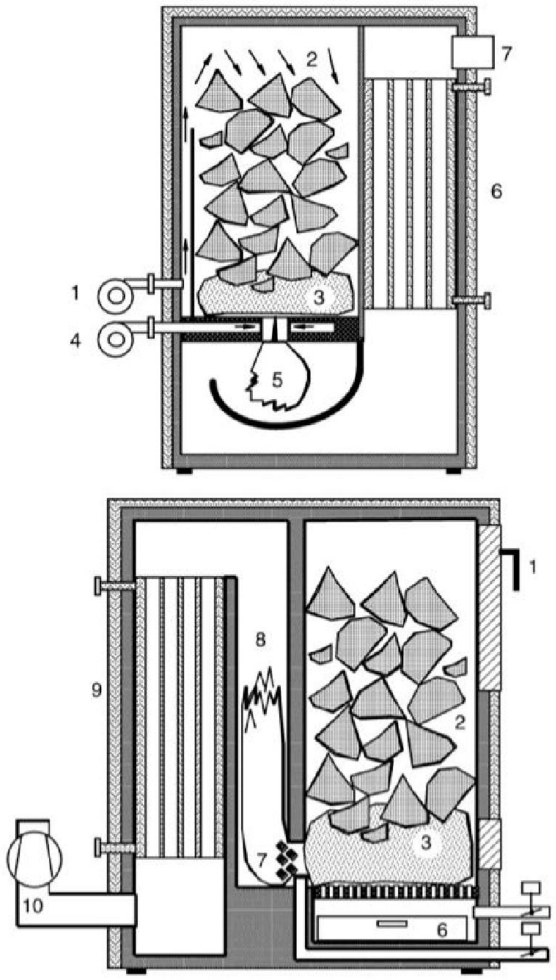

Figure 2: Downdraft boilers with inverse combustion of logwood and with enforced airflow and air supply with primary and secondary air. Above: 1 – primary air, 2 – fuel hopper, 3 – glow bed, 4 – secondary air, 5 – post-combustion chamber, 6 – heat exchanger, 7 – chimney. Below: 1 – fuel inlet, 2 – fuel hopper, 3 – glow bed, 4 – primary air, 5 – secondary air, 6 – ash bin, 7 – mixing zone, 8 – post-combustion chamber, 9 – heat exchanger, 10 – chimney [17]

3. INITIAL DESIGN OF SMALL-SCALE GASIFICATION BOILER

Figure 3 shows the initial design of a small-scale gasification boiler. In the design, wood logs are adequately gasified. However, the problem arises during the combustion of the product gas. High levels, i.e., high emissions of carbon monoxide (CO) were measured. In two weeks of testing, the carbon monoxide CO emissions were in the range of 2500 to 3000 ppm. Two reasons caused the problem. These are unstable control of primary and secondary air and relatively large distance between the gasification and combustion zones. When a small amount of fuel remains in the gasification zone, the primary air flows with ease through the gasification chamber. Due to a lower flow resistance, the amount of primary (gasification) air increases. That causes a more intense uncomplete oxidation in the gasification zone. At that point, the control of the secondary (combustion) air becomes a problem. The flow through the fuel bed and the design of air canals cause a large difference between flow resistances of the primary and secondary air. The primary air is used for oxidation in the gasification zone, whereas, the secondary air is introduced for the complete combustion of the gas phase. The huge difference in the resistances causes the unstable control of two electro motors, which control two valves that regulate the amounts of the primary and secondary air. The other problem is caused by the rapid cooling of the incompletely oxidized gas phase. The cooling prevents the total burnout of the gas phase. The low residence time and the low temperature make unfavoured conditions for the complete oxidation of the gas phase. The subcooling happens because the gas path is too long from the gasification zone to the zone where the secondary air is introduced. Because of the decrease in temperature and inadequate gas flow, incomplete combustion and increased CO emissions occur.

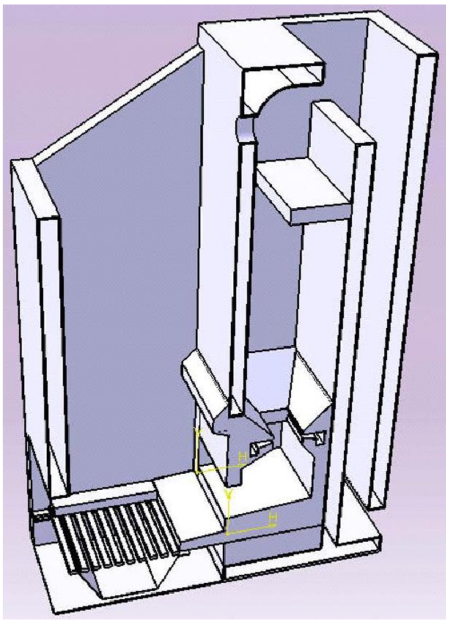

Figure 3: A cross-section view of the initial design of a small-scale gasification boiler

4. CFD MODELLING

This paper aims to present a CFD (Computational Fluid Dynamics) simulation of a 25 kW wood-log-fired water boiler with the use of preheated air. The new design should solve the problem presented in the previous heading. The appropriate distribution of the primary and secondary air and adequate air preheating are the main tasks that are tested by the use of the CFD model. The tool used for the CFD simulation was based on the commercially available software, ANSYS CFX 18.1.

Based on the reference [18], the entire domain of the wood-log-fired water boiler can be divided into gasification and combustion zone.

This heading also describes the boiler geometry, the used mesh, fuel properties, boundary conditions, and air staging configurations.

4.1. Description of the boiler geometry and mesh

For the CFD simulation, the design of the wood-log-fired water boiler shown in Figure 4 was simulated. The ANSYS Design Modeler software and ANSYS Meshing software were used for the wood-log-fired water boiler geometry simulation and numerical grid generation [19].

To improve the shortcomings of the initial design, a new air introduction system has been designed. The new concept of the boiler uses preheated primary and secondary air. Primary air flows through the hottest zone, cools the hearth (position 3 in Figure 4), and is introduced from the opposite sides (9) of the combustion chamber (2). The secondary air (8) is introduced through a large number of orifices (10). The concept is used in the present 25 kW wood-log-fired water boiler. The dimensions of the gasification chamber (1) are: 400x520x145 mm (length, width, and height). The influence of the position and size of the deflector plate (position 4 in Figure 4) affects the emissions of pollutants and leads to higher/lower velocities of the flue gas, which is found in reference [20]. After the initial oxidation reactions, the obtained gas should be immediately in the contact with preheated airflow (secondary air). As the gas is at this stage laden with particulates, their and combustibles in the gas phase burning together should happen from position 10 to position 3 in Figure 4. The intention is to elongate the flame, reduce its temperature and consequently decrease the NOx emissions.

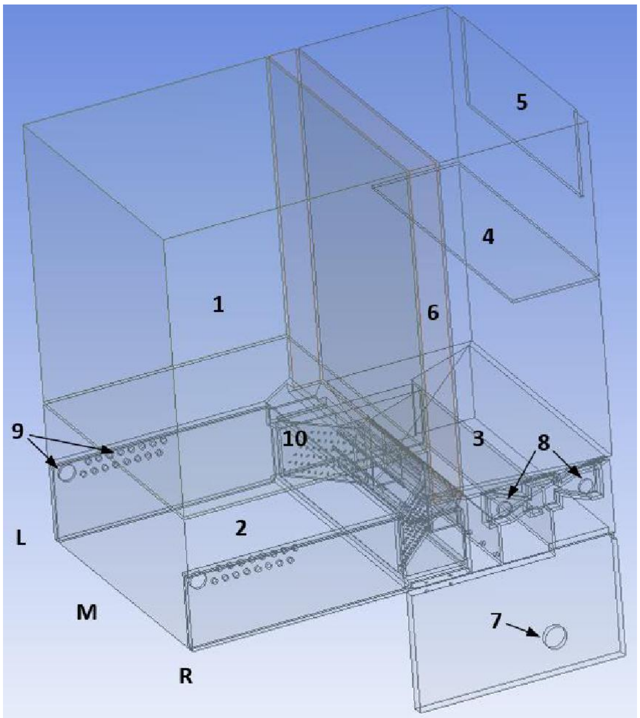

Figure 4: Individual parts of the wood-log-fired water boiler. 1 – fuel import area, 2 – gasification chamber, 3 – combustion chamber, 4 – deflector plate, 5 – flue gas exit, 6 – water channel, 7 – primary air inlet, 8 – secondary air inlets, 9 – primary air inlets to the gasification zone, 10 – secondary air inlets to the combustion zone

Figure 5 shows a detailed 3D fine mesh grid that was used for the numerical simulation. The number of elements is approximately slightly larger than 15 million.

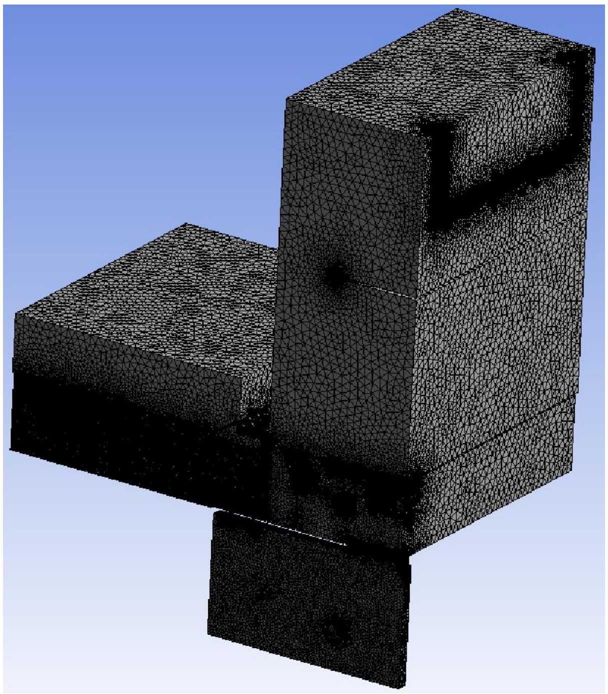

Figure 5: Representation of the 3D fine mesh grid

Table 1 shows the details of the mesh.

Table 1: Details of the mesh

Statistics	
Nodes	2799678
Elements	15137173
Mesh Metric	Average
Element Quality	0.84241
Aspect Ratio	1.8268
Orthogonal Quality	0.86365

4.2. Fuel properties

The most important fuel properties which give the first impression of a certain fuel are given by proximate and ultimate analysis, heating value, and ash fusion point [2]. Beechwood of different lengths was used as the test fuel. Their proximate and ultimate analyses were not done, but the composition of dry beech wood was taken from the database Phyllis2 [21] and is shown in Table 2. The average moisture content of 19.3 wt.% in fuel was measured using Testo 606-1 device and was determined as the arithmetic mean of at least 50 measured values.

Table 2: Properties of the fuel used [21]

Proximate analysis	
Moisture content [wt.%]	19.3
Ash content [wt.%]	0.49
Ultimate analysis	
Carbon [wt.%]	48.35
Hydrogen [wt.%]	5.86
Oxygen [wt.%]	44.98
Nitrogen [wt.%]	0.31
Sulphur [wt.%]	0.02
Heating value	
Net calorific value (LHV) [MJ/kg]	19.07
Gross calorific value (HHV) [MJ/kg]	20.25

4.3. Boundary conditions

The excess air λ is determined using the following equation [22]:

$$\lambda = \frac{20.9}{20.9 - O_2}. \quad (1)$$

The excess air of 1.5 was used. With this excess air, the oxygen content in the flue gas of 7% is obtained. This is a typical value for this kind of boilers. Based on the reference [17], the primary air ratio (λ_{prim}) of 0.8, and the secondary air ratio ($\lambda_{\sec}$) of 0.7 were chosen.

The burning rate of the fuel of 0.001457 kg/s was calculated based on the nominal power of the boiler 25 kW, the LHV of the fuel, and assumed efficiency of 90 % [23]:

$$\dot{B} = \frac{Q}{LHV \cdot \eta}. \quad (2)$$

Based on the air ratios and the fuel-burning rate, the airflows at 293 K are: 0.002304 kg/s and 0.001249 kg/s for the primary and secondary air, respectively. These were calculated by [24]:

$$\dot{m} = \rho \cdot A \cdot v = \rho \cdot \pi \cdot \left(\frac{d}{2}\right)^2 \cdot v. \quad (3)$$

In Eq. (3), the air density is taken to be 1.2041 kg/m^3. The geometry of the openings for the primary and secondary air was calculated based on the assumed velocities: 1.5 m/s for the primary and 2 m/s for the secondary air.

4.4. Air staging configurations

The required primary air for the gasification process is introduced into the gasification chamber through 34 holes (2 larger ones with a diameter of 30 mm, and 32 smaller holes that are 10 mm in diameter) located laterally on both sides of the chamber (Figure 6). The trajectory of the primary air around and below the combustion chamber is shown in Figure 6. The goal was to preheat the primary air before it enters the gasification chamber. The amount of primary air is controlled by a control valve driven by an electric motor.

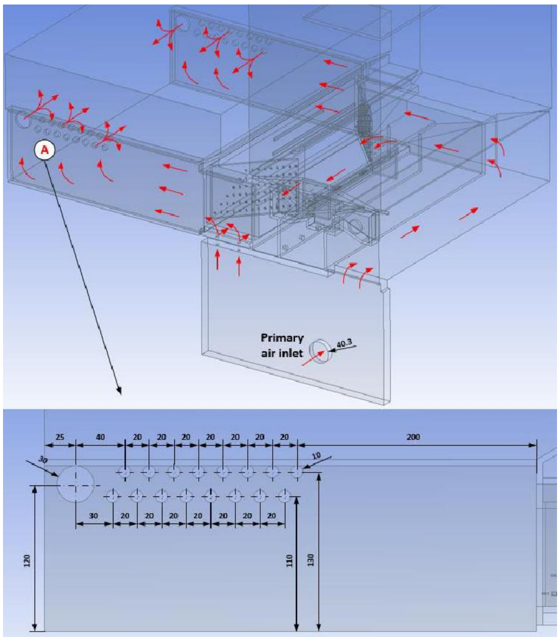

Figure 6: The primary air distribution to the gasification chamber

The shortest distance between the primary and secondary openings is 20 cm. The secondary air is introduced by an array of openings that are shown in Figure 7.

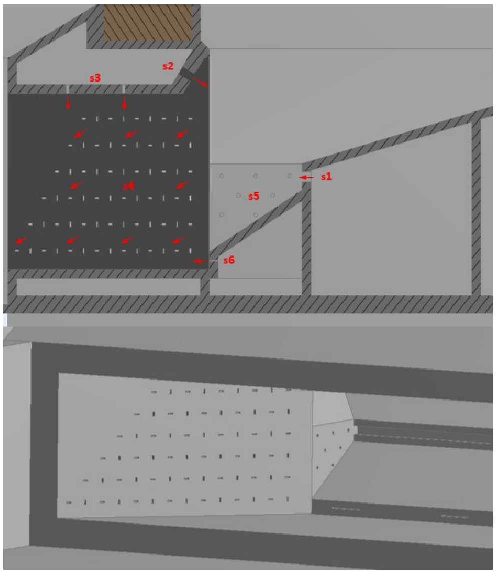

Figure 7: The secondary air distribution to the combustion chamber through the many openings

5. RESULTS AND DISCUSSION

Numerical simulations have been performed on the design shown in Figures 4 and 7. to investigate the influence of air staging on the distribution of the primary and secondary air. Figure 8. shows the simulation results.

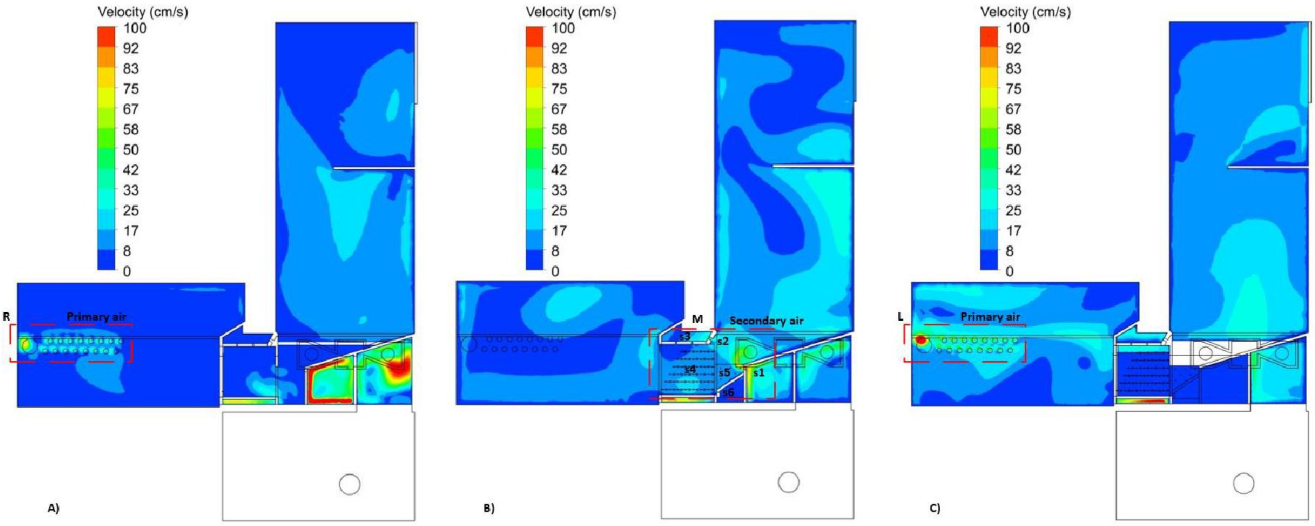

Figure 8: Air velocity field. A – primary air velocity (R), B – secondary air velocity (M), and C – primary air velocity (L)

In the presentation of the results in Figure 8., the priority is given to the velocity fields of the primary and secondary air. The numerical simulation was modeled with the help of 2,799,678 nodes and 15,137,173 elements. The k-epsilon model was used in the Ansys CFX software assuming a pressure of 1 bar in the firebox.

The primary air path (Figure 6.) favors the side (position 9 in Figure 4.) opposite to the primary air inlet (position 7 in Figure 4.). Based on the simulation, it was noticed that there is an uneven velocity field in the chamber that is located in the gasification zone. Figure 8. C shows the primary air (L) velocities (framed by a red dashed line) in the range from 0.67-1.2 m/s, whereas Figure 8. A shows the primary air (R) velocities (framed by a red dashed line) in the range from 0.6-0.8 m/s. The numerical simulation shows that the obtained results differ from the expected for the primary air. Compared with the desired air velocity of 1.5 m/s, the simulated values are lower. In both cases, the highest velocities were achieved through the 2 larger holes that are 30 mm in diameter. These holes are placed at the end opposite the air entrance (see Figure 8. A)

Figure 8.B shows the velocity field for the secondary air (M). In this case, also, the obtained results are contrary to the expected ones of 2 m/s. As can be seen, the secondary air favors the air curtain (position s1 in Figure 8.B) located in the combustion zone with velocities in the range from 0.6-1.1 m/s. The aim of the air curtain (position s2 in Figure 8.B) was to divert the flame and the velocities were in the range of 0.6-0.67 m/s. The secondary air velocities (positions s3, s4, s5, and s6 in Figure 8.B) were in the range from 0.08-0.25 m/s. It can also be seen that the velocity field is less favorable because there is a "short circuit" to the convective part of the boiler on the underside of the deflector plate. Also, in the combustion zone, the secondary air velocity field shows that the highest flow velocities were at the air curtain (position s1 in Figure 8.B), which is good because it favors the uplift of ash and unburned particles towards the convective part of the boiler.

6. CONCLUSION

The initial design of the small-scale gasification boiler had large carbon monoxide (CO) emissions, which were in the range of 2500 to 3000 ppm with a flue gas oxygen content of 7 %. Incomplete combustion of gas due to its rapid cooling has been identified as a cause of excessive emissions of pollutants. The paper aimed to answer the question of how to improve the second stage of the combustion process in the boiler. Multi-stage combustion of wood logs by the use of preheated air was envisaged. The preheating of the primary air by passing around and under the combustion chamber, before entering into the gasification chamber through a total of 34 holes. The primary air ratio is 0.8 and it should be maintained close to 0.7-0.8, which is found in reference [17]. It has also been proposed to preheat the secondary air and introduce it into the combustion chamber through the many openings. The goal was to improve the mixing of the secondary air and the gas that is coming from the gasification chamber. It is important to note that the flow resistances of the primary and secondary air should be on the same order of magnitude because the low resistance of the secondary compared with the primary air can lead to a negative impact on the control of the combustion process in such types of boilers. The numerical simulation showed that the primary and secondary air streams enter the chambers at slower than desired velocities. This problem should be solved by an additional redesign of the hearth. A gradual introduction of air in a larger area should reduce carbon monoxide (CO), nitrogen oxides (NOx), and the emissions of volatile organic compounds (VOC), whereas the diversion of the flame should reduce the emissions of particulate matter.

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