Experimental Investigation of an 18-kW-Wood-Log-Fired Gasification Boiler

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Abstract: Compared with other solid biofuels, fuelwood as the oldest biomass fuel source, requires less processing, which results is smaller processing and transportation emissions. Oppositely, the air pollutant emissions are larger due to inefficient combustion control influenced by an uneven size distribution and different moisture content. The previous facts explain why biomass gasification boilers are mainly used for steady-state combustion. In this kind of operation, the majority of air pollutant emissions are emitted during the start-up and stoking processes. In the paper, experimental investigations of an 18-kW-wood-log-gasification boiler are presented. The boiler uses proven technology: two dampers for the control of gasifying and combustion air, an extractive fan and downdraft gasification. Even this, proven technology could be substantially improved regarding the efficiency and emission by the use of small modifications. The most creative modifications could be made by the use of: (i) refractory insets in the combustion zone and (ii) different turbulators and small wings in the convective part of the boiler. The first are used to promote complete combustion and radiant heat transfer whereas the second are used to support convective heat transfer and to reduce particulate matter emissions. The examined boiler implemented these modifications and fulfilled the most stringent annexes of the standard EN 303-5:2012 regarding the efficiency and pollutant emissions.

Keywords: wood logs, boiler, gasification, emissions, experimental investigation

1. Introduction

Initiatives for renewable energy usage [1-6] contributed to a greater and more diverse use of biomass energy. Standardization of biofuels [7] and stringent environmental protection norms [8,9] influence new construction solutions in boiler building industry as old industry branch, relatively accommodated to the current technology needs. Despite the standardization and emergence of various solid biofuels, fuelwood is still a very important energy source, since there are many economic and environmental comparative advantages to other biofuels in favour of using fuelwood. Comparing to other solid biofuels, fuelwood requires less additional energy for processing and transportation, which decreases prices, as well as parasite emission of the pollutants in manipulation and transportation processes. Despite these positive aspects, disadvantages of fuelwood in comparison to other biofuels are: higher and often variable moisture content, difficulties in the combustion process automation, more difficult combustion process control (non-stationarity of the combustion process) and higher emissions of the pollutants.

To use positive properties and solve problems that occur during fuelwood usage, so called gasification boilers emerge at the market. These boilers use multi-stage combustion: at the first stage the wood is gasified (incompletely combusted) while in the second stage the fuel gas (produced gas) is completely combusted. Small power systems use only fixed –bed gasification (entrained bed gasification processes), whereas at higher power, fluidized bed and entrained flow gasification is used. Fixed-bed gasification is dominated by downdraft (or concurrent) systems, which have proven to be the most reliable in gasifiers with DC power. Figure 1 shows the most frequently used designs of the gasification chambers and combustion gasification boilers [10]. Almost as a rule, gasification chamber is, at the same time, a fuel storage bunker for thermal capacities up to 50 kW. Gasification chamber is, for most designs [11-16], at least partially coated with some refractory material. Most of this material is located as a barrier between gasification and combustion chambers due to the extremely high temperatures in that part of the firebox.

The role of refractory barrier (lining) in the gasification process in also important due to its thermal accumulation which provides additional energy for gasification when using wood with higher moisture contents (above 15 wt%). Therefore, this refractory lining allows short term rises in the moisture contents. However, these boilers are not reliable over a long period of time while operating during gasification of wood with moisture contents higher then approximately 25 wt%.

The shape of refractory lining allows engineering freedom in designing of these boilers and crucially affects the completeness of combustion. The shapes of gasification and combustion chambers and their interconnections also represents the first measure of defence against the increased emission of particulate matters. Figure 1 represents frequently used designs of gasification boilers, in which downdraft gasification take place. The designs A and B have higher emissions of particulates than design C, while the design D can have variety of particulate emissions, depending of the shape of refractory inset 5.

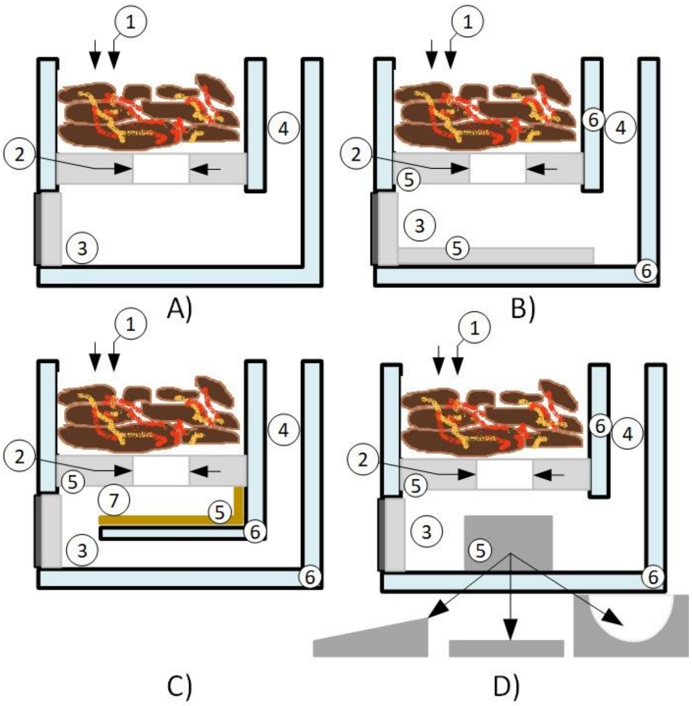

Figure 1. Frequently used designs of gasification boilers, in which downdraft gasification take place. A, B, C, and C are different designs (analysed systems with direct gasification of fuelwood): 1 – primary air (for gasification) and gasification chamber, 2 – secondary air (for combustion of fuel gas), 3 – combustion chamber, 4 – convective part of the boiler, 5 – elements of refractory ceramics, 6 – channels for water flow, 7 – intermediate chamber

Generally, gasification boilers have no problem with the emission of gaseous pollutants (CO, C_xH_y, NO_x) at stationary mode. A bigger problem are the emissions of particulate matters that depend on the boiler design and flow characteristics inside it: from the introduction of primary air to the flue gas exit from the boiler. Due to the relatively good combustion in the stationary operating mode, such boilers are used for combustion in only one operating mode with approximately constant thermal power and they are generally paired with hydronic heat accumulators. However, the problem with emissions occurs in non-stationary operating modes: during the start-up and stoking processes while operating. Number of the available literature provides the solution of these problem [17]. Its structure is very complex, given that those boilers are used in households. Boiler consists of three fans (two that blow in air and one and one that ensures constant flow of flue gas at the exit, which also maintains constant pressure in the boiler), centrifugal combustion chambers and absorbers whose role is the absorption of pollutant emissions during start-up. The absorbed hydrocarbons and particulates are located in a zone of relatively high temperatures and, with the help of excess air, are subject to oxidation over a long period of time.

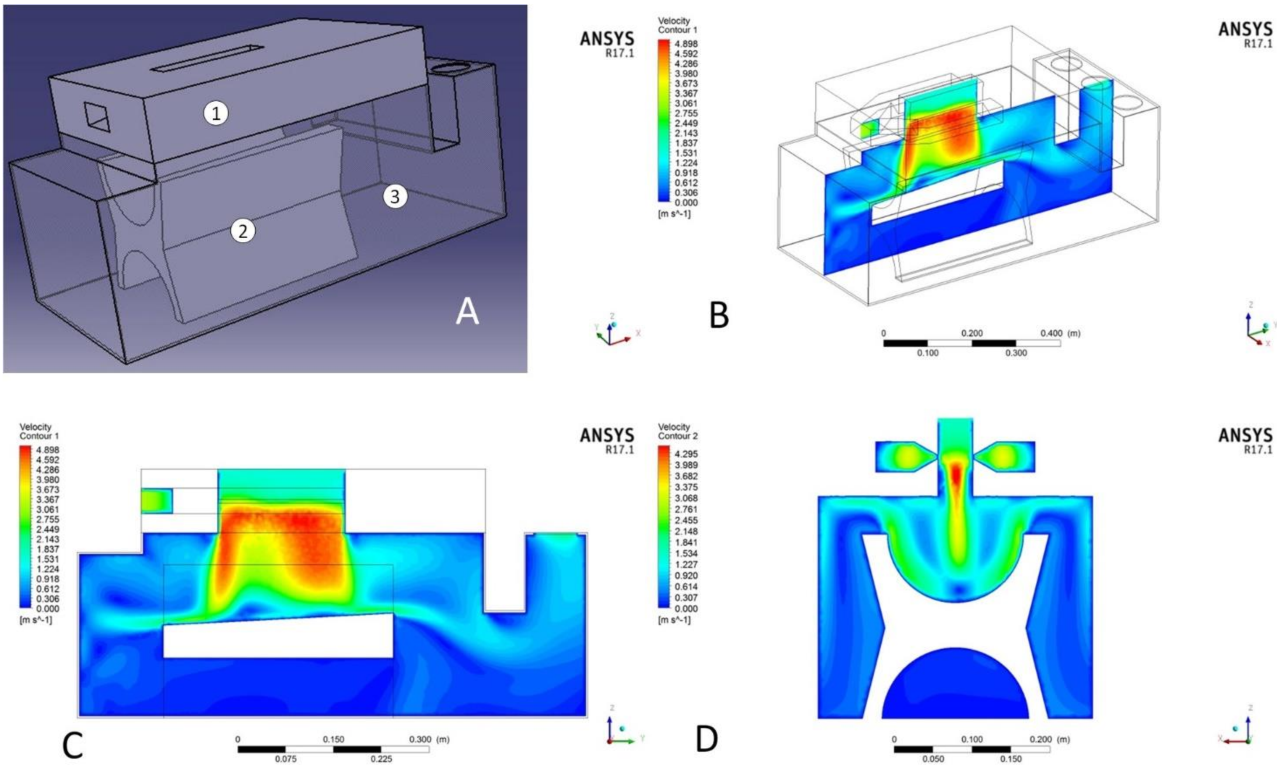

Figure 2. Firebox obtained after the simulation and modelling of an earlier version of boiler. A – isometric view of the firebox in which: 1 – refractory plate that separates gasification and combustion zones, 2 – refractory insert, 3 – firebox, B, C, D - velocity fields in the combustion zone [10]

Figure 2 shows the solution obtained by modelling and simulation of the examined design as shown in Figure 1. C. The main objection to the proposed solution was the centring and fixing of the refractory insert in the combustion zone of the boiler. Therefore, this paper presents the implemented solution where the insert is fixed at the back side (downstream) as shown in Figure 3. The favourable geometry of the refractory inserts can significantly improve the heat transfer in the combustion zone and reduce the number and complexity of technological operations in boiler production. The insert positioned as shown in Figure 3 protects the combustion chamber walls from high flame temperature, diverts the ash to the combustion-chamber door and allows most of the flue gas to go to the front door of the combustion chamber while the remained flue gas “overflows” through two side gaps and contributes to lower uptake of solids. Upon leaving the combustion zone, the flue gas flows upward through the convective part of the boiler, which consists of 3 tubes equipped with turbulators. They have a dual role: to improve the heat transfer from flue gas to water and serve to remove impurities (particulate matters and tar) from the inner surfaces of pipes.

The boiler has one extractive fan and two dampers. The first damper controls the flow of primary (gasification) air and is controlled so that the flue gas outlet temperature is maintained at 150 °C. The second damper controls the secondary, i.e. air used for combustion of flue gas. For each boiler design and given fuel, there is one optimum range in which secondary air flow should be kept. In the investigated boiler, the best emissions were obtained for the 6.9% of oxygen in the flue gas. Table 1 shows the basic technical characteristics of the investigated boiler. The objective of this paper is to present experimental investigation of the described boiler and to present a simple solution for a relatively small reduction of particulate matter emissions.

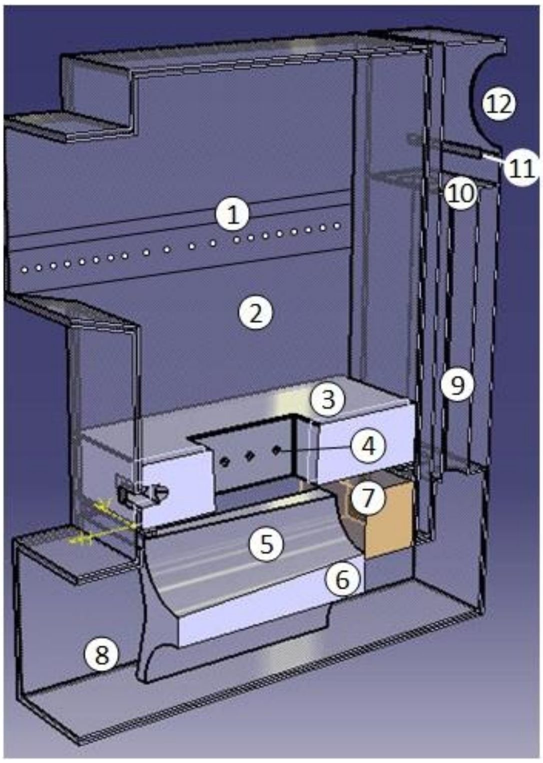

Figure 3. Examined boiler design. 1 – primary (gasifying) air introduction points, 2 – gasification chamber (wood-log reservoir), 3 – refractory plate, which is used to separate gasification 2 and combustion 5 zones and have secondary air introduction points 4, 6 – refractory inset, 7 - refractory protection used for positioning of 6 and protection of boiler walls, 8 – firebox, 9 – convective part of the boiler, 10 – tubes equipped with turbulators, 11 – small wing, 12 – flue gas exit.

Table 1. Main technical date of the examined boiler

Manufacturer	**"RADIJATOR INŽENJERING" DOO**
Nominal output	**18.00 kW**
Reduced heat output	**not applicable**
Max operating pressure	**3 bar**
Max operating temperature	**90** ℃
Boiler class	**5**
Water volume	**100 lt**

2. Experimental investigations

The investigation of the gasification boiler was done in accordance with standard EN 303-5:2012. Table 2 shows the test conditions in the laboratory of the company "RADIJATOR INŽENJERING" in Kraljevo during boiler examination. Table 3 presents experimental results and the measuring equipment used.

A large number of tests have been performed and the paper presents the best stable values, for which a high probability of repeatability is guaranteed. The investigation was performed to adjust the boiler's automatic control, which controls the two dampers and one fan based on the flue gas outlet temperature and the amount of oxygen in the combustion products.

2.1. Fuel characteristics

Table 2 contains the characteristics of test fuel, beech, with average moisture content of 13.87%. Generally, the recommendation is to use as dry firewood as possible in gasification boilers. In practice, firewood with a moisture content of 20 wt% is considered dry, while wood with a moisture content of less than 15 wt% is very difficult to obtain by drying outdoors. In order to meet the strict country-specific annexes of EN 303-5: 2012, boiler manufacturers use as dry wood as possible, processed into identical logs with hexagonal cross sections of equal size and length, as shown in Figure 4. Such wood processing is used only for experimental testing and is used to provide stationary conditions in the gasification zone and to avoid the problems of bridging and sintering of materials in the gasification zone. Namely, wood gasification processes are threatened by bridging, which results in uneven gas flow due to the creation of larger passages for easier gas flow in some reactor parts and the compression of the high temperature material and the sintering of larger pieces in the second part.

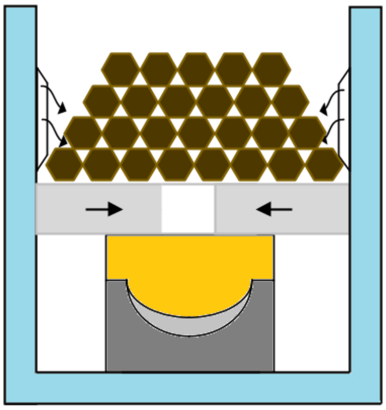

Figure 4. Wood logs with hexagonal cross sections of equal size and length used to prevent bridging and slagging in the gasification zone and reduce emissions

Table 2. Test condition of the reported examinations presented in Table 3.

Ambient temperature	**20.3 ℃**
Humidity	**not required**
Nominal mode – duration **Beginning** **End**	**2.03 h** **10.40 h** **12.47 h**
Atmospheric pressure	**1001.1 hPa**
Flue gas velocity	**1.82 m/s**
Draft	**11.6 Pa**
Flue gas temperature	**151.8 ℃**
Oxygen O_2	**6.91 %**
Chimney diameter	**0.31 m**
Area	**0.075 m^2**
Points	**1**
Diameter of the nozzle	**12 mm**
Hard beech. Test report for the fuel **Net calorific value** **Moisture**	 **15.85 MJ/kg** **13.87 %**

3. Results

Table 3 and Figures 5 and 6 represent investigation results brought down to normal conditions (0°C and 101.325 Pa) and dry flue gas with 10 wt% of oxygen O_2. The results were brought down based on the eqs. (1) and (2):

$$CO\left(\frac{mg}{m^3}\right) = \frac{21 - O_{2ref}}{21 - O_2} \cdot CO(ppm) \cdot \left(\frac{28}{22.4}\right) \quad (1)$$

$$NO_x\left(\frac{mg}{m^3}\right) = \frac{21 - O_{2ref}}{21 - O_2} \cdot NO_x(ppm) \cdot \left(\frac{46}{22.4}\right), \quad (2)$$

where the values are given in mg/m_N^3, measured in ppm and referent oxygen value O_{2ref} amounts 10% in dry flue gas under the normal conditions.

Table 3. Experimental results

Performance		**Requirements of the standard for class 5**	**Measuring equipment**
Nominal output	18.07 kW		
CO /10% 0_2/	126.57 mg/Nm^3	Max. 500 mg/Nm^3 (Acc. EN303-5:2012 4.4.7)	HORIBA VA-300
Dust /10% 0_2/	18.44 mg/Nm^3	Max. 40 mg/Nm^3 (Acc. EN303-5:2012 4.4.7)	
OGC /10% 0_2/	5.02 mg/Nm^3	Max. 20 mg/Nm^3 (Acc. EN303-5:2012 4.4.7)	SIEMENS FIDAMAT 6
NO_x /10% 0_2/	175.75 mg/Nm^3 (87.24 mg/MJ)	n/a Max. 100 mg/MJ (Acc. Table C4 EN303-5:2012)	HORIBA VA-300
Efficiency	90.30 %	Min. 88.26 % (Acc. EN303-5:2012 4.4.2)	

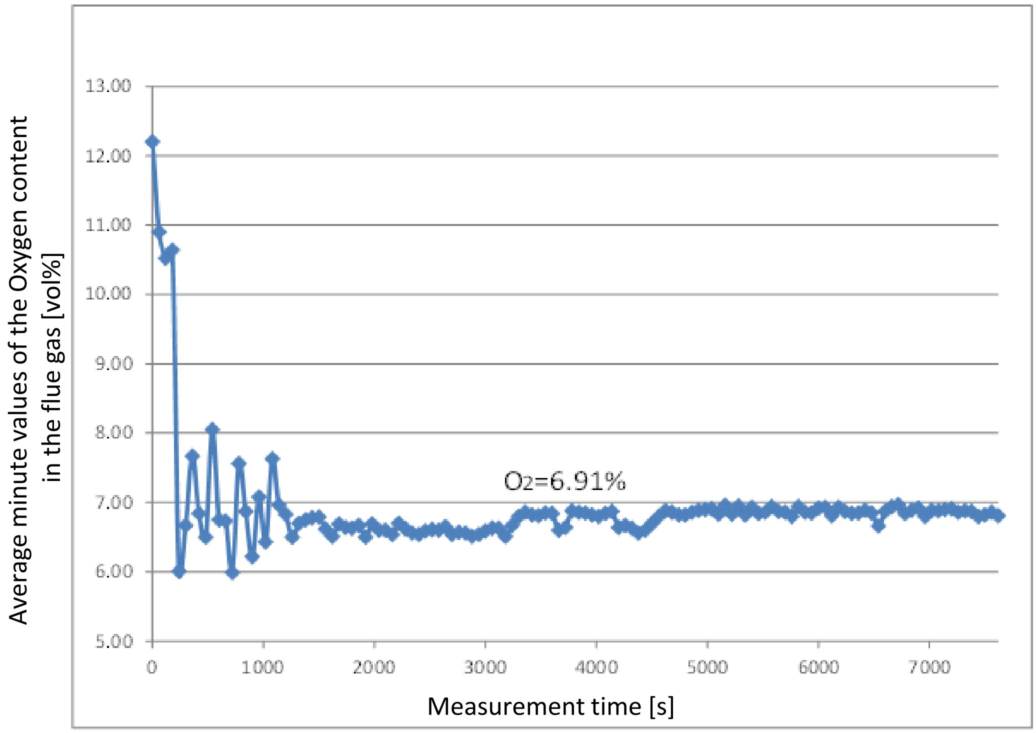

Figure 5. Average minute values of the oxygen content in the flue gas during the experimental investigation

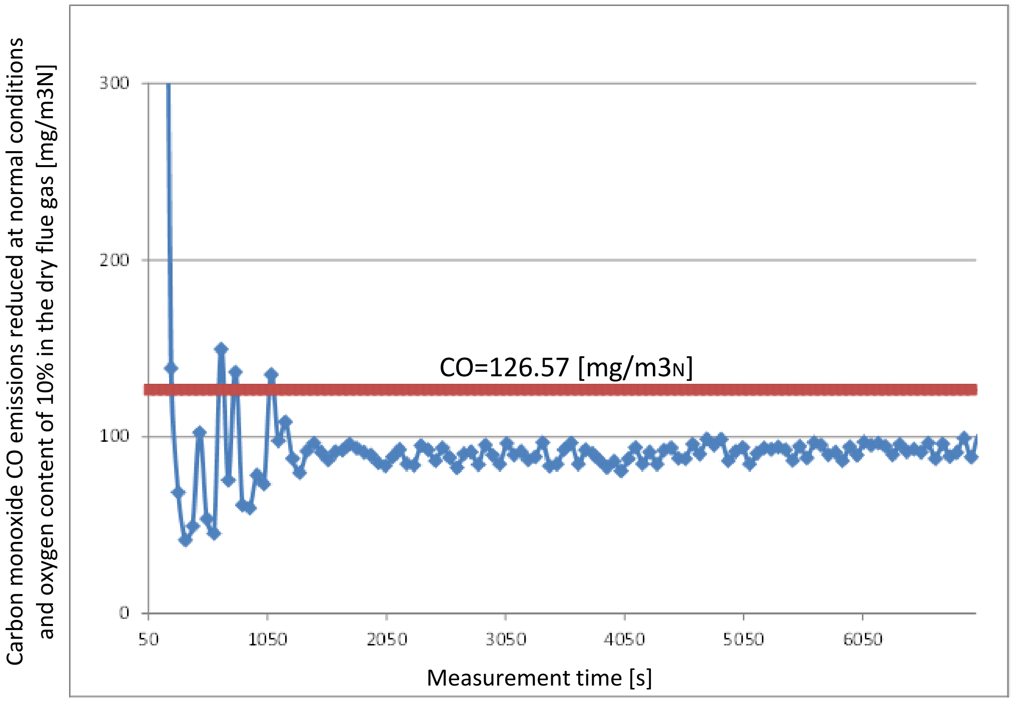

Figure 6. Average minute values of carbon monoxide CO emissions during the examination (CO content in the dry flue gas at normal conditions (0℃, 101325 Pa) and with the oxygen content of 10%)

Test results indicate that the boiler meets the highest class of standard EN 303-5: 2012 and all its annexes. In order to obtain the presented results, some changes had to be made. In order to avoid fuel stoking during the tests, the boiler had to have a large enough storage bunker and used an additional structural element to reduce particulate matter emissions. The design presented in Figure 5 does not solve the problem of initial emissions and emissions that occur during boiler loading. It behaves the same as most of the structures shown in Figure 1.

Under these conditions, the control is not stable. However, the correct selection of refractory inserts can introduce stationary conditions very quickly. Another way to prevent these emissions, which represents up to 90% of total emissions of gas pollutants, is to apply a different concept of the combustion control It is possible to reduce emissions by applying different control algorithms during these periods.

An example is that, during these periods, the dampers occupy the exactly assigned positions depending on the period, and that the fan (regulating the number of rotations) provides the exactly assigned flow rate over time. Only after these periods, the control would be in accordance with the set output temperature and set oxygen content in the flue gas. The second method refers to the concept of construction and control already described in the introduction chapter [17], whose main decision is to stop emissions in the boiler and to prevent them over the time with complete combustion. The emission limit values, technology maturity, and the cost of the particular design dictate which concept will be implemented in the boiler. Figures 5 and 6 show the relatively narrow ranges of CO and O_2 emissions during boiler performance.

3.1. Emissions of particulate matters

The particulate matter emissions are the direct consequence of: the type of fuel being burned, the way of combustion and the design of boiler, i.e. its flow characteristics. Without additional protection against the emission of particulate matters, these emissions were ranged from 18.3 to 24.2 mg/m_N^3 in 10 experimental tests with beech-wood of different moisture content. The average emission during these tests was 21.2 mg/m_N^3 ± 10%. Given the relatively large relative error of these measurements, the boiler met a very strict limit of 20 mg/m_N^3. To meet emission limits for particulate matters of all annexes of EN 303-5: 2012, it was decided to experiment with additional obstacles.

Figure 7 shows the two proposed technical solutions. The technical solution shown in Figure 7. B is simple and consists of one additional wing whose role is to prevent a short connection between the convective pipes and the boiler outlet. This obstacle acts as a resistance that extends the path of the flue gas inside the boiler and slows down the gas flow at the very exit of the boiler. It also reduces uptakes from the convective pipes and allows the boiler to be easily cleaned and turbulators shaken off.

Table 3 shows that the emissions of particulate matters of the investigated boiler with the additional wing was 18.44 mg/m_N^3 ± 10%. This is average value of 8 experimental trials which varied within very narrow limits. Since this was satisfactory solution, no experimental testing of the solution shown in Figure 7. C was performed. This solution would use the principle of impactor and is a little more complicated to perform and undesirable because it would make it difficult to clean the boiler.

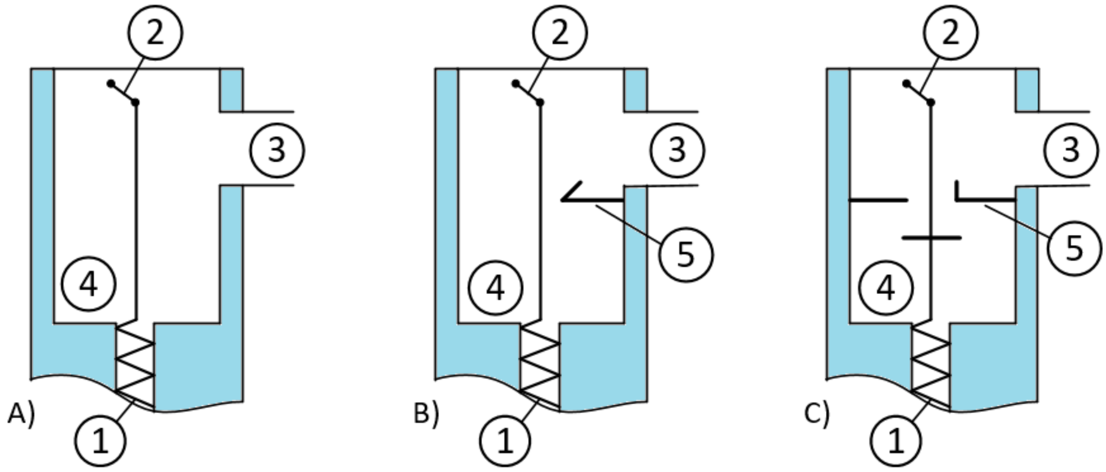

Figure 7. Schematic of the flue gas exit from the boiler. A – without additional parts for lowering of particulate emissions, B – with an additional wing for the reduction of particulate emissions, C – with impactor like structure for preventing particulate emissions. 1 – turbulators in convective part of the boiler, 2 – shaking mechanism, 3 – flue gas exit, 4 – flue gas exit chamber, 5B – additional wing, 5C – impactor like structure.

4. Conclusions

Very small modifications to standard design solutions make it possible to improve efficiency and reduce emissions from the small hydronic boilers. As much as this part of the technique is developed, each solution can be further improved. The use of refractory inserts and accessories can result in reduction of the overall pressure drop, the heat exchange surface and the number of technological operations.

The boiler design solution, investigated in the paper, met the most stringent requirements of the annexes of EN 303-5: 2012. These changes in the boiler design were small and encompassed the usage of the refractory insert of a specific shape and one outlet wing to prevent particulate matter emissions. The applied refractory insert was specific because it directs unburnt larger pieces towards the front door of the boiler and does not concentrate the flame to one side only, but allows it to spread. It is unproven assumption that this shape of insert is the cause of the satisfactory NO_x emissions, despite the high flame temperature associated with this kind of fuel. Like most “classical” design solutions, the design solution presented in the paper did not solve the issue of huge emissions during start-up and stoking of the gasification boilers. For this kind of solutions different concepts are needed.

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