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POLLUTANT CONCENTRATIONS FROM TWO-STAGE THERMAL CONVERSION OF PINE WOOD LOGS IN A 25 KW BOILER WITH FIXED AIR SUPPLY

A study and further analysis of the two-stage process of burning pine wood logs (gasification and wood gas combustion) in a 25 kW heating boiler were performed. The air stream for combustion was set manually and was constant throughout the given test run. The values of the carbon monoxide, hydrocarbons and nitric oxide in the flue gas were measured. The correlation between the concentration level of these pollutants and the temperature in the wood gas firing nozzle was established, as well as the link between the nitric oxide and carbon monoxide concentrations and the influence of the oxygen concentration in the combustion air on the carbon monoxide emission.

Keywords: wood combustion, pollutant emission, heating boiler

Introduction

Burning biomass in low heat output boilers

Different fuels have their own characteristics, arouse specific kinds of problems and thus require particular considerations when burned. Interesting study results in the area of pollutant emissions from burning biomass and other fuels can be found in recent studies [Musialik-Piotrowska et al. 2010; Musialik-Piotrowska, Kolanek 2011; Hardy et al. 2012]. As far as wood is concerned, the lowest emission of incomplete combustion products is obtained while burning wood pellets, especially in comparison with wood logs. It is well known that the main criteria for complete burnout are temperature, time, and turbulence (TTT). A smaller size of pellets, as compared to logs, makes it easier for the air to reach the fuel during combustion. The fact that the pellets are fed automatically and do not require the opening of the combustion chamber during feeding keeps the temperature raised,

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as opposed to what happens during manual wood log feeding. In spite of the favourable characteristics of wood pellets in terms of a reduction in incomplete combustion products, small heating boilers are commonly fed with wood logs, especially pine, due to their widespread availability and low price, which is precisely why they are the subject of this study.

The limited availability of high quality and cheap wood pellets in Poland (which are currently used in power plants) has aroused interest in agricultural biomass pellets as fuel for heating boilers with a low heat output. Agricultural biomass is known for its low ash melting temperature, which is why it should be burned at a temperature lower than 700°C [Werther et al. 2000], in order to avoid the production of slag, which hampers furnace operation and the combustion process. In addition, chlorine content is an important factor in biomass combustion as it can form KCl that melts at a low temperature. Therefore, it is recommended that additives are used, such as $Ca(OH)_2$ or dolomite, which react with the chlorine and impede KCl formation [Poskrobko et al. 2010a,b, 2012].

When burning biomass, it is worth remembering that its lower heating value is smaller in comparison with hard coal, which translates to a lower temperature in the combustion chamber. This results from the fact that at the first stage of combustion, it releases as much as 80% of volatile organic compounds (VOC), the rest being charcoal, whereas for hard coal it is only 20%, the rest being coke. This makes the flue gas from biomass combustion reach the cold heat exchange surfaces and get cooled even quicker. Therefore, in order to maintain the flue gas inside the combustion chamber for an adequate period of time, wood-fired combustion chambers should be of considerable size, much bigger than the ones supplied with hard coal.

For the reasons described above, boilers supplied with biomass, especially wood, require bigger combustion chambers screened with ceramic elements and heat exchange surfaces located outside of the combustion chambers, in order to maintain a high temperature and ensure a higher heat output. Unfortunately, however, wood-fired domestic heating boilers – for economic and logistical reasons – are equipped with small combustion chambers with walls functioning directly as heat exchange surfaces which are reached by the flue gas much too quickly. As a consequence, the air is cooled and the combustion process is hampered. For this reason, the time of the burning process in the combustion chambers of low heat output boilers is much shorter than in the combustion chambers of boilers with a higher heat output. Therefore, conditions for the complete burnout of such a large quantity of volatile compounds are insufficient.

As this study examines low heat output heating boilers (<50 kW) typically used in domestic heat stations, it is important to note that these boilers, in comparison with higher heat output boilers (>1MW), present a much larger emission of incomplete combustion products (carbon monoxide, hydrocarbons and sooth) per produced energy unit. It is estimated that in Germany in 2000, the share of small-scale wood combustion systems contributing to the emission of incomplete combustion products was between 16 and 40%, although their total energy production was only approximately 1% [Knaus et al. 2000]. These numbers have since changed as currently more modern boilers are being used in Germany, however this does show the scale of the problem. In Poland, the emission ratio per energy unit is similar or even higher, as cheap boilers of simple and old design, with low heat efficiency and lacking a proper automatic air stream regulation system with an oxygen probe (lambda sensor) are much more commonly used. The high emissions of incomplete combustion products from old-fashioned small wood-fired heating boilers has been confirmed in bibliographical sources [Johansson et al. 2004]. It is therefore of extreme importance to examine the possibility and methods of reducing pollutant emissions from these particular kinds of boilers.

Two-stage combustion of wood logs

Wood logs can be burned either with a flame on the grate or in a two-stage combustion process that includes wood gasification in the gasification chamber at a temperature of approximately 250–300ºC with air shortage, and the subsequent wood gas combustion in the nozzle at a temperature of 650–900ºC. In two-stage combustion, a reduced oxygen feed to the gasification chamber ensures that the logs smoulder rather than burn, whereas the nozzle needs to be supplied with enough air to conclude complete combustion of the wood gas.

Modern two-stage thermal conversion boilers are equipped with a fan and automatic air regulation system with an oxygen probe installed at the flue gas outlet. In case the air concentration in the flue gas is lower than expected, the regulation system increases the air stream supplied for combustion by increasing the fan resolutions. The placement of the fan at the flue gas outlet creates negative pressure and therefore helps avoid flame combustion in the gasification chamber as the flame that could arise is "sucked in" from the gasification chamber to the wood gas firing nozzle.

In Poland, however, these kinds of modern boilers are still rare. Meanwhile, old-type two-stage residential combustion boilers are more commonly used. In such boilers, the gasification process is poorly controlled: air is supplied to the gasification chamber and the gas firing nozzle by a fan located at the inlet and the flue gas is evacuated to the chimney by its natural draught (no fan used). This creates the risk of introducing too much air to the gasification chamber and creating conditions for flame combustion (overpressure). As these boilers lack an automatic air flow regulation system with an oxygen probe, an adequate amount of air is set manually at the beginning according to the chimney draught, by regulating the valve while observing the gasification chamber through a sight glass. During boiler operation, however, the fan resolutions and air stream are constant. Old-type boilers for two-stage wood log thermal conversion with the properties described above are commonly used in Poland for heating purposes in detached houses, especially in villages and smaller towns. A typical example of one is the Orlan 25, a boiler produced by Eko Vimar Orlański, and its slightly modified version, the Vitolig 150, sold under the Viessmann brand, both yielding a heat output of 25 kW. The second boiler was used in the present study.

Materials and methods

The experiments were carried out in a full-scale heat station located in a laboratory belonging to Poznań University of Technology (the Department of Heating, Air Conditioning and Air Protection in the Institute of Environmental Engineering) in conditions resembling the ones existing in domestic boilers. The equipment used in the study was a Vitolig 150, a two-stage wood log thermal conversion boiler with a heat output of 25 kW, commonly used in residential houses in Poland (fig. 1).

Fig. 1. Vitolig 150 log boiler – scheme and view

The study examined pine wood logs with the dimensions of 10 cm in diameter and 40 cm in length. The properties of the given wood were examined in an accredited laboratory with the following results: the lower heating value of the dry wood – approx. 19 MJ/kg, moisture – 24% (measured as water mass divided by dry wood mass), lower heating value of the wet wood – approx. 13.9 MJ/kg, element contents: carbon – 49%, hydrogen – 6.1%, nitrogen – 0.13%, oxygen – 43.2%, ash content – approx. 1%.

The measurement methods were as follows: the gas pollutant concentrations in the flue gas downstream of the boiler, as well as the flue gas temperature, were measured continuously using a Vario Plus (MRU) flue gas analyzer (Germany). The oxygen, nitric oxide and nitrogen dioxide (NO_2) concentrations were measured using electrochemical cells. The carbon monoxide and hydrocarbon (presented as methane) concentrations were measured using the infrared procedure. The NO_x concentration was calculated using the gas analyzer by summing up the concentration of NO (transformed to NO_2) and NO_2, and it was presented in the form of NO_2 concentration. At the temperature in the nozzle of up to 1000ºC (which is the case in this study), nitrogen dioxide formation is negligible, however in pollutant concentration measurements from boilers, the NO_x concentration is customarily indicated in order to be able to compare it with the Polish standard [PN-EN-303-5:2004]. The temperature in the gasification area, as well as in the wood gas firing nozzle, was measured with radiation shielded thermocouples PtRhPt connected to a temperature meter for value comparison. The heat received by the boiler water and boiler heat output was measured using an ultrasonic heat meter. The boiler heat efficiency was calculated as heat transferred to the boiler water divided by fuel mass, then multiplied by the fuel lower heating value. The values obtained were compared with the heat efficiency values calculated using the flue gas analyzer (based on chimney loss which depends on the flue gas temperature).

During the study, 10 batches of pine logs were loaded into the boiler. The total burnout time of each batch was approx. 1.5 hours. Parameter values were registered in the computer every 3 seconds. For analysis purposes, however, values from 2 selected batches (of 25.740 and 25.120 kg) were taken into account. These batches were chosen for reasons of diversity in the mean values of their oxygen concentration and temperature in the nozzle. The different values are presented in the table and as dots in the figures. Diagrams were used to illustrate the influence of these two parameters on pollutant concentrations in the flue gas. In addition, the variation of the measured parameters in time and the correlation between the nitric oxide and carbon monoxide concentrations in the flue gas were analyzed.

Results

The results obtained in the study are presented below for the two selected batches of burned pine logs. The mean values of the measured combustion parameters (oxygen concentration, air excess ratio, gas pollutant concentrations, temperature in the nozzle, boiler heat output, and boiler heat efficiency) are shown in table 1. Figs. 2 and 6 present the variation in time of the parameter values (oxygen concentration, pollutant concentrations: nitric oxide, nitrogen oxides, hydrocarbons, air excess ratio, temperature in the nozzle) for the first and second batch, respectively. Figs. 3 and 7 illustrate the correlation between the aforementioned gas pollutant concentrations and the temperature in the wood gas firing nozzle. In figs. 4 and 8, the mutual relation between the concentrations of nitric oxide and carbon monoxide can be observed, whereas in figs. 5 and 9 the carbon monoxide concentration was presented as a function of the oxygen concentration in the flue gas. The figure pairs described above refer to the first and second batch, respectively. The dots marked in the diagrams (except fig. 2 and 6) were obtained in the course of the simultaneous measurement of the different parameters.

Table 1. Mean parameter values for pine wood logs burned in Vitolig 150 boiler

Batch	1	2
Mass [kg]	25.740	25.120
O_2 concentration [%]	12.7	10.0
Air excess ratio λ	2.3	1.8
CO concentration [mg/m^3] (10% O_2)	6125	3136
NO concentration [mg/m^3] (10% O_2)	161	109
NO_x concentration [mg/m^3] (10% O_2)	247	167
HC concentration [mg/m^3] (10% O_2)	858	55
Temperature in the nozzle [°C]	521	683
Boiler heat output [kW]	18.1	20.4
Boiler heat efficiency [%]	64	74

CO – carbon monoxide
O_2 – oxygen
NO – nitric oxide
NO_x – nitrogen oxides
HC – hydrocarbons

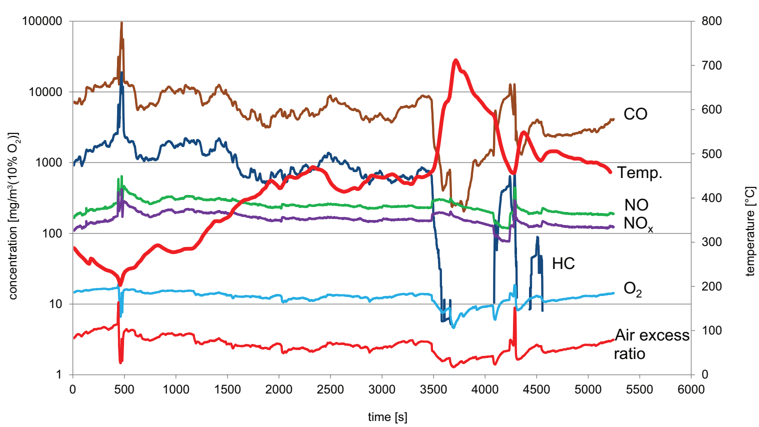

Fig. 2. Variation of the measured parameters in time (oxygen and pollutant concentrations in the flue gas, temperature in the nozzle, air excess ratio) during pine wood log combustion in wood gasification boiler (Vitolig 150); first batch

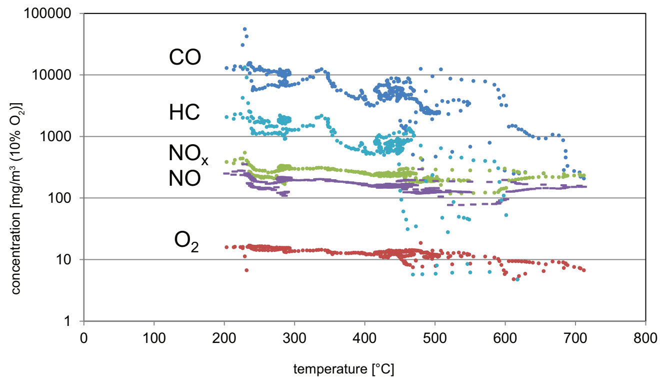

Fig. 3. Oxygen and pollutant (CO, NO, NO_x, HC) concentrations in the flue gas versus temperature in the wood gas firing nozzle; first batch

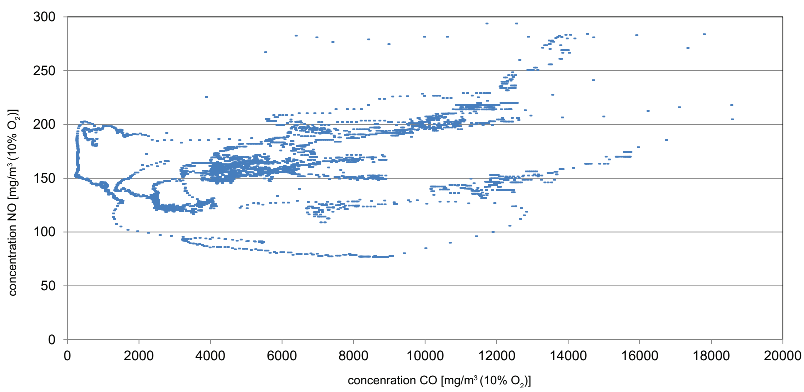

Fig. 4. Nitric oxide concentration versus carbon monoxide concentration in the flue gas; first batch

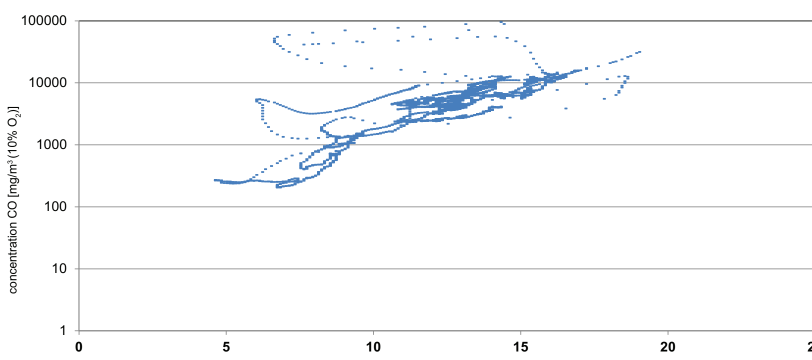

Fig. 5. Carbon monoxide concentration versus oxygen concentration in the flue gas; first batch

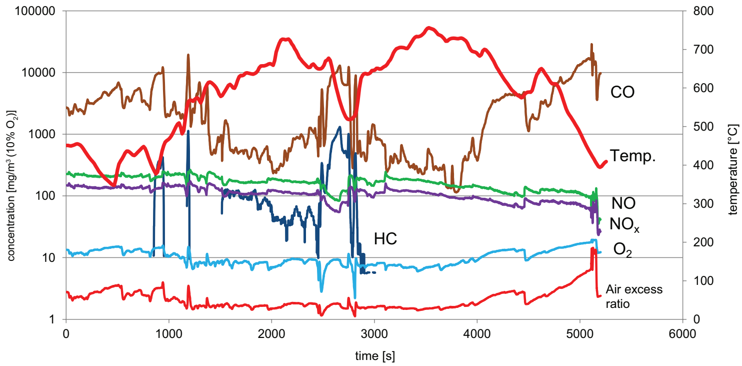

Fig. 6. Variation of the measured parameters in time (oxygen and pollutant concentrations in the flue gas, temperature in the nozzle, air excess ratio) during pine wood log combustion in wood gasification boiler (Vitolig 150); second batch

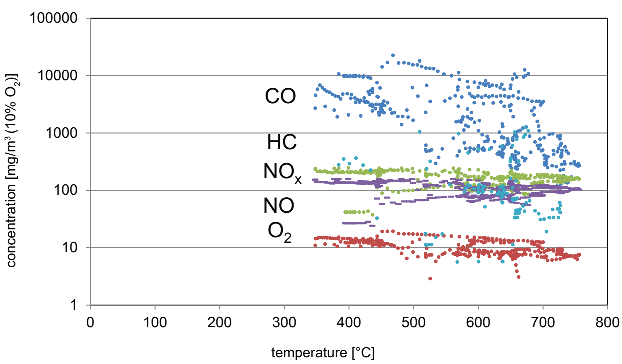

Fig. 7. Oxygen and pollutant (CO, NO, NO_x, HC) concentrations in the flue gas versus temperature in the wood gas firing nozzle; second batch

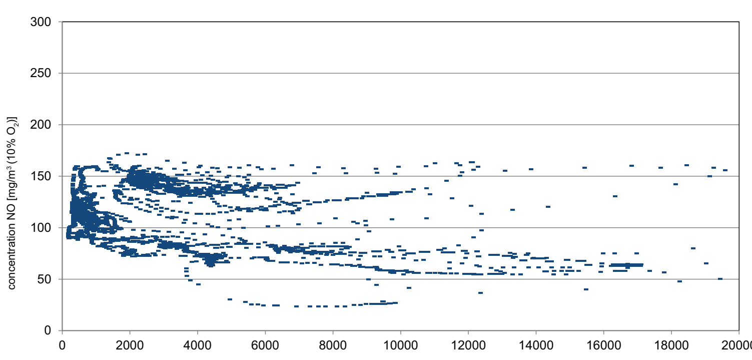

Fig. 8. Nitric oxide concentration versus carbon monoxide concentration in the flue gas; second batch

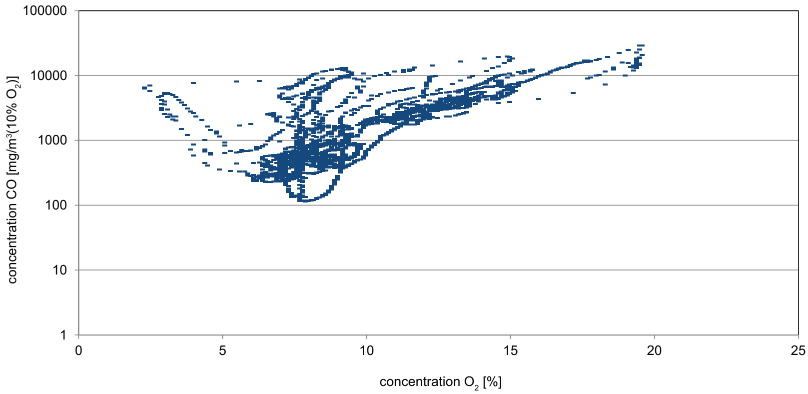

Fig. 9. Carbon monoxide concentration versus oxygen concentration in the flue gas; second batch

Discussion

The results shown in table 1 convey the mean values of the measured parameters for the batches of pine logs which presented the most diverse results. All the concentration values are presented for 10% O_2 content in the flue gas. It was observed that the carbon monoxide emission in the case of the first batch was almost twice as high (6125 mg/m^3) as in the second batch (3136 mg/m^3). The carbon monoxide level in the first batch exceeded the limit value of 5000 mg/m^3 established in the Polish standard [PN-EN-303-5:2004]. It is commonly known that oxygen and temperature are important factors conditioning complete combustion. In addition, in our study they seem to have influenced the pollutant emission levels. The high emission of carbon monoxide observed in the first batch was related to the low temperature in the nozzle (521ºC) and an excessive oxygen concentration in the flue gas (12.7%). Some previous studies have revealed that the optimum temperature in the nozzle for this specific kind of furnace should range between 750 and 850ºC [Juszczak 2007]. In the case of the second batch, the oxygen concentration was 10% and the temperature in the nozzle was 683ºC.

Although the NO and NO_x concentration value is not regulated by the Polish standard [PN-EN-303-5:2004], it can be assumed that it should not exceed 400 mg/m^3 [Kubica 1999]. As shown in table 1, these concentrations are much lower in both batches.

The hydrocarbon concentration in the flue gas was significant in the case of the first batch (853 mg/m^3) and could have potentially (including other sources of organic carbon, e.g. soot) caused the breach of the organic carbon limit value defined in the Polish standard [PN-EN-303-5: 2004]. In the case of the second batch, the hydrocarbon concentration was very low (55 mg/m^3). During the experiments, the boiler heat efficiency was not high: 64 and 74% for the first and second batch, respectively.

On analyzing variations in the measured parameters in time for the first (fig. 2) and second batch (fig. 6), considerable changes in the pollutant concentrations can be observed, especially in the case of the carbon monoxide and hydrocarbons. This is due to the fact that the wood gas generation and its combustion in the nozzle was variable in time. Log mass in the gasification chamber gradually decreased as the batch was burned, causing wood logs to move down gravitationally and constantly change their arrangement in the gasification chamber. As a result, significant instantaneous changes in the concentrations of carbon monoxide and hydrocarbons in the flue gas occurred. In terms of the correlation between the carbon monoxide concentration and the temperature, this relation is clear in the case of the second batch: the carbon monoxide concentration decreased as the temperature in the nozzle increased (fig. 6), whereas in the first one (fig. 2) it was not as noticeable, as the temperature in the nozzle was not high enough for the carbon monoxide to by properly oxidize to carbon dioxide.

The influence of the temperature variation on the oxygen concentration and pollutant concentrations is shown in figs. 3 and 7 for the first and second batch, respectively. The experimental set-up worked with a fixed air stream supply system, meaning that no automatic combustion air stream regulation with an oxygen probe was applied. As a consequence, the intensity of the wood gas combustion increased, influencing both the temperature in the wood gas firing nozzle (which gradually increased) and the oxygen concentration (which decreased). In general terms, the temperature in the gasification area ranged between 300 and 350ºC for both batches. The concentrations of carbon monoxide and hydrocarbons decreased with the increasing temperature. Although the oxygen concentration decreased, it did not affect the correlation between the temperature and the pollutant concentrations, as it was still high enough.

Particularly worth noting is the nitric oxide concentration (as well as the concentration of nitrogen oxides). As previously proven [Kordylewski 2000], at a temperature of up to 1000ºC, the nitric oxide concentration depends mostly on the fuel nitrogen content but also, to a lesser extent, on the oxygen concentration and temperature in the combustion area. Usually, an increase in both the oxygen concentration and the temperature causes a reduction in the nitric oxide concentration. Nitrogen oxides behave analogically. In the present study, however, as can be observed in figs. 3 and 7, the influence of the oxygen concentration on the nitric oxide concentration seemed to be predominant. Therefore, although the temperature increased, the nitric oxide concentration still increased because of the simultaneously decreasing oxygen concentration.

As far as the correlation between the carbon monoxide and nitric oxide is concerned, it was very different for the two pine log batches studied. While burning the second batch, as the temperature was high enough, it was observed that the increased carbon monoxide concentration resulted in a decrease in the nitric oxide concentration (fig. 8). This shows the previously found reducing influence of the carbon monoxide and hydrocarbons on the nitric oxide [Kordylewski 2000]. In the case of the second batch (fig. 4), due to the low temperature in the nozzle and higher oxygen concentration, as the carbon monoxide concentration increased, so the nitric oxide concentration decreased.

Figs. 5 and 9 show the correlation between the carbon monoxide and oxygen concentrations. As previously proven [Nussbaumer 2003], while the oxygen concentration increases during fuel combustion, the carbon monoxide concentration initially decreases and then, after reaching its minimum (at a certain optimum oxygen concentration level, specific for each type of furnace), it starts to increase. As can be observed in figs. 5 and 9, for the type of furnace studied and fuel, the lowest carbon monoxide concentration was obtained at the oxygen concentration level of 7%. This observation is particularly important and might be useful in case the analyzed boiler was to be modernized and equipped with an automatic air flow control with an oxygen probe.

Conclusions

During the two-stage thermal conversion of pine wood logs of significant moisture in a 25 kW boiler with no automatic air stream regulation with an oxygen probe, a significant emission of carbon monoxide and hydrocarbons may be observed, and the boiler may demonstrate low heat efficiency. In order to reduce the carbon monoxide and hydrocarbon concentrations, it is important to burn drier wood, and maintain the temperature in the wood gas firing nozzle above 650°C. Further reduction of the concentrations of carbon monoxide and hydrocarbon, as well as a boost to the boiler heat efficiency, would require boiler modernization: installing an automatic air stream regulation system with an oxygen probe and induced draught fan located downstream of the boiler. The oxygen concentration would then have to be set to approx. 6–7%, which is the value found to be optimum for the type of boiler studied.

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