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CORRELATION BETWEEN AIR FLOW RATE AND POLLUTANT CONCENTRATIONS DURING TWO-STAGE OAK LOG COMBUSTION IN A 25 KW RESIDENTIAL BOILER

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It can be expected that there is a considerable correlation between combustion air flow rate and the concentrations of carbon monoxide, hydrocarbons and nitrogen oxide in the flue gas. The influence of temperature and oxygen concentration in the combustion zone on the concentrations of carbon monoxide, hydrocarbons and nitrogen oxide in the flue gas, for high and low combustion air flow, was analysed. Oxygen concentration for which the concentration of carbon monoxide is the lowest was determined, as well as the mutual relation between carbon monoxide and nitrogen oxide concentration.

Keywords: wood combustion, pollutant emission, heating boiler, heat station

1. INTRODUCTION

In the recent years there has been a growing interest in biomass as fuel for residential boilers for reasons related to environment-friendly policies. Basic information and general analysis of the biomass combustion process can be found in (Nussbaumer, 2000). A review of small biomass combustion systems was presented in (Hartman et al., 2006). Some interesting studies of biomass fired boilers were also conducted using a retort furnace (Knaus et al., 2000, Musialik-Piotrowska et al., 2010). Out of different biomass types of fuel, wood pellets are most desirable, giving the lowest pollutant emission and enabling automation of the fuel supply process. Unfortunately the availability of high quality and reasonably priced wood pellets on the Polish market is quite limited and therefore agrobiomass pellets are lately quite frequently used (e.g. straw, hay, sunflower husks, coffee husks) (Verma et al., 2012). In case of agrobiomass pellets, however, it is quite challenging to obtain pollutant emission as low as in case of wood pellets due to the fact that at temperatures of approx. 750 °C slag is produced, hampering furnace operation (Gible et al., 2008 and Juszczak et al., 2012).

The cheapest and most accessible biomass fuel are wood logs, which is why wood log boilers are still in common use in Poland. Generally speaking, in case of wood log combustion carbon monoxide emission is much higher than in case of wood pellet combustion (Juszczak, 2014; Qui, 2013; Verma et al., 2009; 2011; 2012). Therefore studies have been conducted to examine the optimal conditions for wood log firing that would enable reducing pollutant emission (especially carbon monoxide and hydrocarbons) for this specific type of fuel. This is also the purpose of the presented study.

Similar studies examining pollutant emissions using wood log fired boilers with a heat output of approx 20 kW were previously conducted (Boman et al., 2011; Johansson et al., 2004; Kjallstrand et al., 2004

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and Olsson et al., 2006). However, these experiments were performed in laboratory conditions in controlled stationary states, in most cases obtaining lower pollutant (mainly carbon monoxide) concentration results than would probably be achieved in real-life conditions. Even lower values are obtained in accredited laboratories (Francisco Josephinum Wieselburg BLT, 2009; 2010), in stationary states during pollutant emission analysis commissioned by boiler producers. In such idealized conditions the values of pollutant (mainly carbon monoxide) concentrations are considerably lower and much higher boiler heat efficiency than could ever be achieved in real-life conditions.

For these reasons, unlike many researchers and laboratories, I have personally focused my work on examining boilers under conditions resembling those existing in domestic boilers. In all my studies special attention has been paid to create conditions as similar to the real ones as possible and therefore simulate domestic boiler operation in Polish conditions (variable heat demand, no oxygen probe air stream regulation). Such conditions can be obtained in a full scale heat station. My previous research analyzed burning coniferous (Juszczak, 2010) and deciduous (Juszczak, 2011) wood logs in the same type of boiler as the one described in this study (Vitolig 150) where attempts were made to reduce carbon monoxide concentration in flue gas with results mostly below the permitted value determined by the Polish-European standard (PN-EN 303-5, 2012). The type of boiler used in this and my previous experiments is a wood gasification boiler that performs two-stage wood log combustion including gasification in the boiler's chamber and product gas (wood gas) firing in a nozzle located in the lower part of the boiler. This process differs from flame combustion of wood on a fixed grate performed by the lowest heat output heating boilers (of less than 50 kW).

Low cost wood gasification boilers of simple and old design, commonly used in Poland, are equipped with a manual air flow rate regulation that can be set before each load of wood logs. In the previous studies (Juszczak, 2010) it could be observed that combustion air flow rate has an impact on gas pollutant concentration level in the flue gas downstream the boiler, so as a consequence this study aims at examining the level of this influence using oak logs as a common type of wood fired in residential boilers in Poland.

In order to ensure optimal conditions for environment-friendly wood log combustion the main goal is to obtain the lowest possible concentration of carbon monoxide and hydrocarbons in the flue gas downstream the boiler. To do so, it is important to make sure the air supplied to the gasification chamber is not excessive. Otherwise the wood log gasification (incandescence) process will transform into flame combustion, in which case the nozzle is mostly fed with flue gas instead of wood gas. Oxygen concentration level in the flue gas allows to obtain the lowest possible carbon monoxide concentration. Most of the time oxygen concentration in the flue gas ranges between 5 and 10% and depends on the furnace quality. If the furnace is properly designed and executed then oxygen concentration is close to 5%, while in case of low quality furnaces this value is close to 10%. Another factor ensuring a proper combustion process is temperature in the product gas firing nozzle, which should be maintained at least at 650 °C, since only above this temperature the conditions for carbon monoxide oxidisation are optimal. Low carbon monoxide concentration in the flue gas can be obtained at the temperature in the nozzle above 750-800 °C.

The aim of the experimental study was to determine the level of influence of the combustion air flow rate on pollutant concentration levels especially carbon monoxide, nitrogen oxides and hydrocarbons in the flue gas downstream the boiler for a low heat output wood log gasification boiler in conditions simulating domestic boiler use with a fixed combustion air flow rate for a given fuel load.

2. EXPERIMENTAL SET UP

The equipment used in the study was Vitolig 150 (Fig. 1), an old design two-stage wood log thermal conversion boiler with heat output of 25 kW, commonly used in detached houses in Poland. Its furnace is composed of a gasification chamber and a nozzle located at its bottom, where the product gas (wood gas) is fired. The heat is received from the flue gases by the gasification chamber walls and flue gas tubular pipes - there heat exchange surfaces are surrounded with water to heat. Combustion air is supplied to both, the gasification chamber and the nozzle, by means of a single fan.

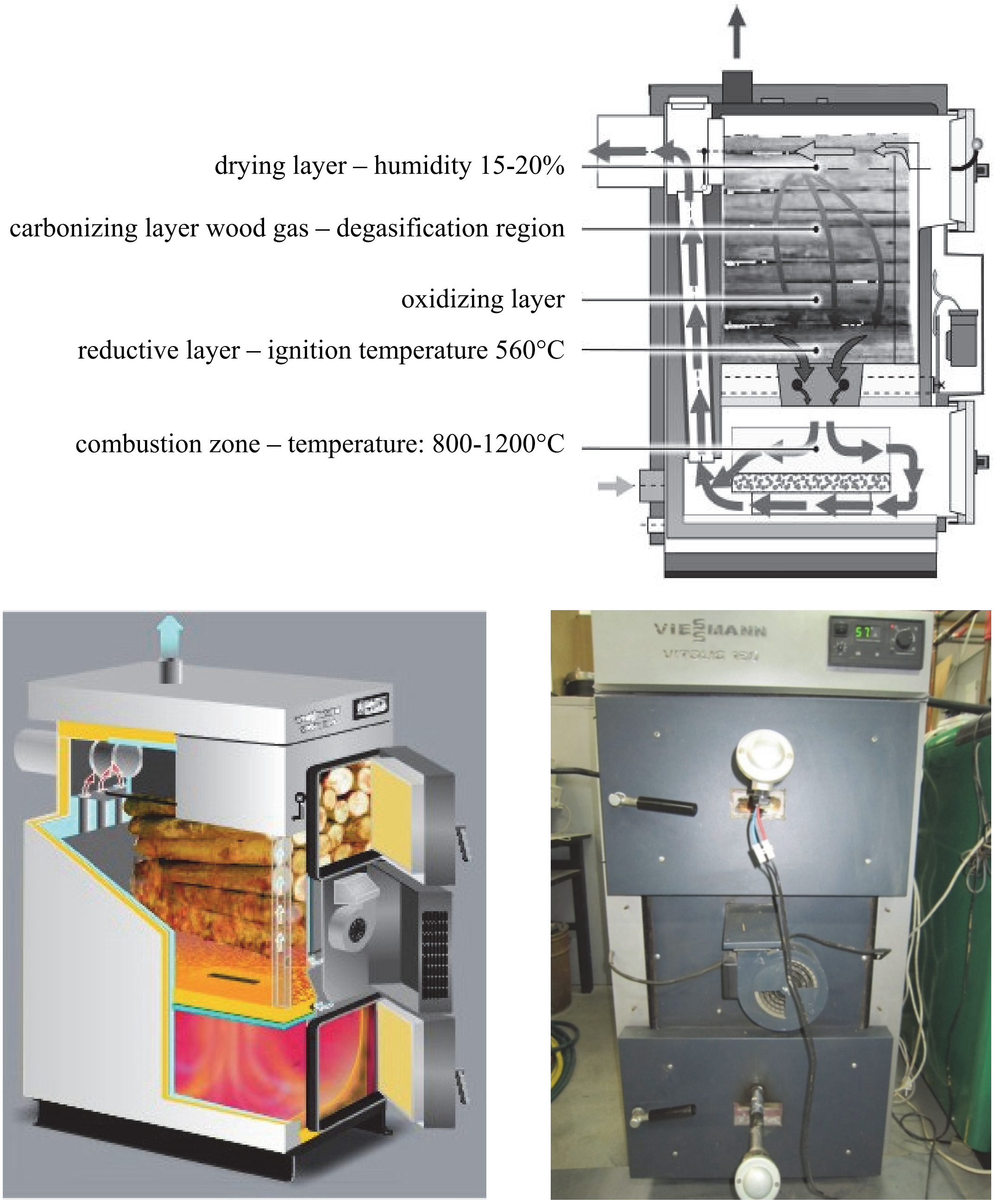


Fig. 1. Vitolig 150 log boiler - scheme and view (during tests)

The proportion of air distributed to these two regions of the furnace is determined by the boiler technical service that sets manually the position of the two diaphragms located in the air inlet channels of the gasification chamber and the nozzle while observing the indications of the flue gas analyser. The end user can however modify the total air flow rate before each fuel load (it cannot be smoothly regulated during the combustion process of a given batch) by adjusting the diaphragm in the inlet to the fan.

The experiments were carried out in a full scale heat station connected to district heating network, heat transfer unit, heat receivers: radiators and water heat storages (Fig. 2). The station is located in a laboratory belonging to the Poznan University of Technology (Division of Heating, Air Conditioning and Air Protection, Institute of Environmental Engineering) and was constructed for the purpose of performing research in real-life conditions, resembling the ones existing in domestic boilers. The schematic layout of the experimental set-up is presented in Fig. 2.

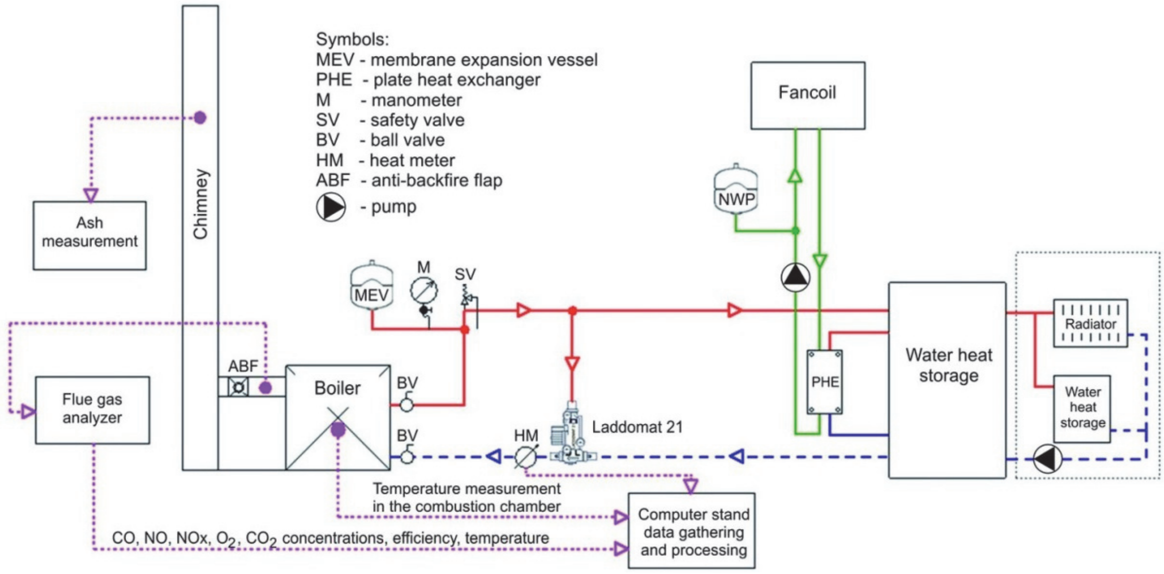


Fig. 2. Schematic layout of the experimental set up – biomass fed heat station and heat receivers

2.1. Material

The study was performed using oak wood logs, including bark, with the dimensions of approx. 500 mm in length and 60-80 mm in diameter and with approx. 28% moisture (the ratio of water mass to wet fuel mass). The properties of the given wood were examined in an accredited laboratory and gave the following results: lower heating value of dry wood measured with calorimetric method - approx. 13.1 MJ/kg.

An ultimate analysis of wood logs used for the experiments is presented in Table 1. Ash content was measured in the laboratory of Poznan University of Technology and was always below 1.3 wt %.

Table 1. Ultimate analysis of wood (performed by an accredited laboratory)

Wood type	chemical element, wt %			
	C	N	H	O
Oak	49.1	0.16	6.1	43.4

2.2. Experimental procedure and measuring equipment

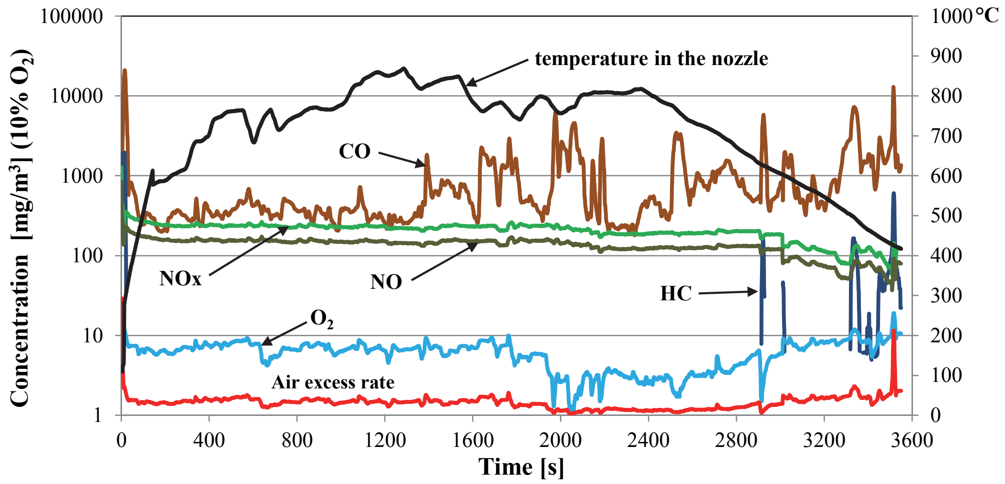
Two oak wood log batches (containing bark) of about 10 kg were fired in the boiler described above. The conditions for the two batches varied in terms of combustion air flow rate - one was higher and one was lower.

Air flow was not measured, instead it was determined by measuring air excess ratio; higher air flow corresponded to a higher air excess ratio. Air stream was chosen empirically. Gas pollutant concentrations in the flue gas downstream the boiler, as well as flue gas temperature, were measured continuously using Vario Plus flue gas analyzer (MRU brand). Oxygen, nitric oxide (NO) and nitrogen dioxide (NO_2) concentrations were measured with electrochemical cells. Carbon monoxide and hydrocarbon concentrations were measured using the infrared procedure. NO_x concentration was calculated with the gas analyzer by summing up the concentration of NO (transformed to NO_2) and NO_2, and it was presented in form of NO_2 concentration. Pollutant concentrations were transformed from ppm to mg/m^3 and were all presented for 10% O_2 content in the flue gas in order to be able to compare it with the Polish-European standard (PN-EN-303-5, 2012). The temperature in the wood gas firing nozzle was measured with a thermocouple PtRhPt that was radiation shielded in order to reduce the negative effect of radiation. The boiler heat efficiency was calculated as heat transferred to the boiler water divided by fuel mass multiplied by fuel lower heating value. The obtained values were confronted with heat efficiency values calculated based on the chimney loss and other estimated heat losses. Heat received by the boiler water and boiler heat output were measured with Kamstrup ultrasonic heat meter. All the measured parameters were recorded continuously and transferred in real time to computer memory, where they were registered every 3 seconds for averaged value calculation.

3. RESULTS

The results obtained during the measurements performed in the heat station are presented below in Table 2 and visualized in Figs. 3-6. Figure 3 compares the variation in time of oxygen concentration, pollutant concentrations and temperature in the nozzle for the two batches fired at lower and higher air flow rate. Figure 4 shows the oxygen and pollutant concentrations versus temperature in the nozzle.

a)



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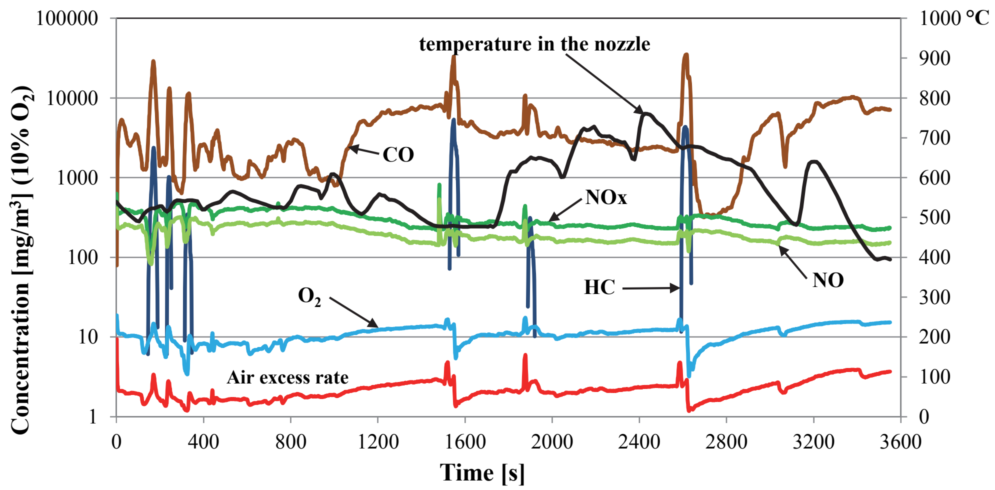

Fig. 3. Comparison of the parameter variation in time (oxygen and pollutant concentrations: CO, HC, NO, NO_x in the flue gas, temperature in the nozzle, air excess ratio) between the two batches fired with (a) high combustion air flow rate and (b) low combustion air flow rate

Table 2. Mean parameter values (oxygen concentration, pollutant concentrations, air excess ratio, temperature in the nozzle, boiler heat output and heat efficiency) obtained during oak log combustion in the boiler Vitolig 150 boiler

Batch	Mass	O_2 concentration/air excess ratio	CO concentration	NO concentration	NOx concentration	Hydrocabon concentration	Temperature in the nozzle	Boiler heat output / boiler heat efficiency
	kg	% / ---	mg/m^3 (10% O_2)				°C	kW / %
1	10.25	12 / 2.2	907	164	251	52	810	24.1 / 65
2	10.42	9/ 1.7	5328	145	220	95	590	16.2 / 43

A correlation between carbon monoxide concentration and nitrogen oxide concentration was presented in Fig. 5, whereas the correlation between carbon monoxide and oxygen concentration was shown in Fig. 6.

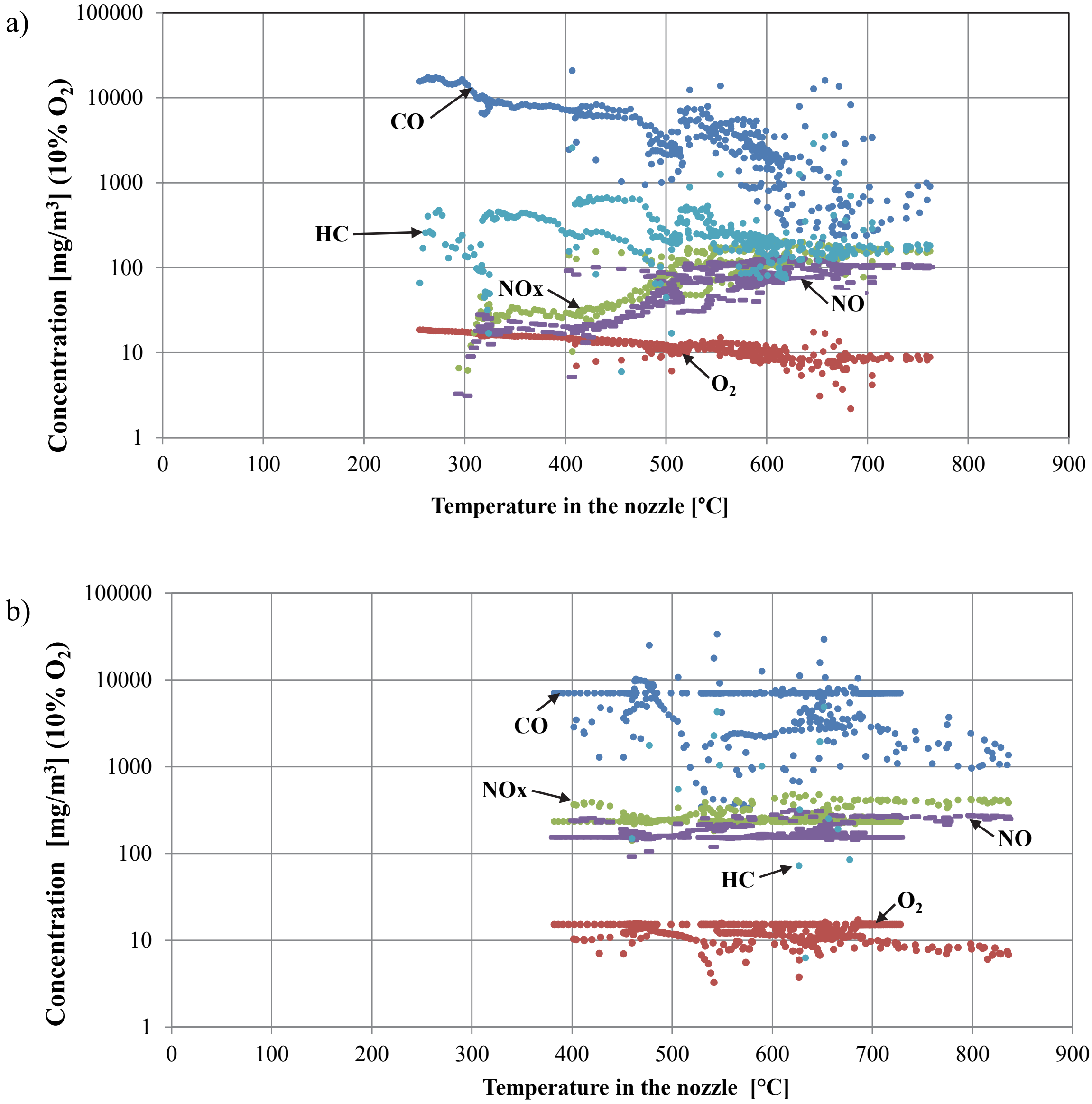

Fig. 4. Oxygen and pollutant (CO, HC, NO, NO_x) concentrations in the flue gas versus temperature in the wood gas firing nozzle/combustion chamber; comparison between (a) the batch fired with high combustion air flow rate and (b) the batch fired at low combustion air flow rate

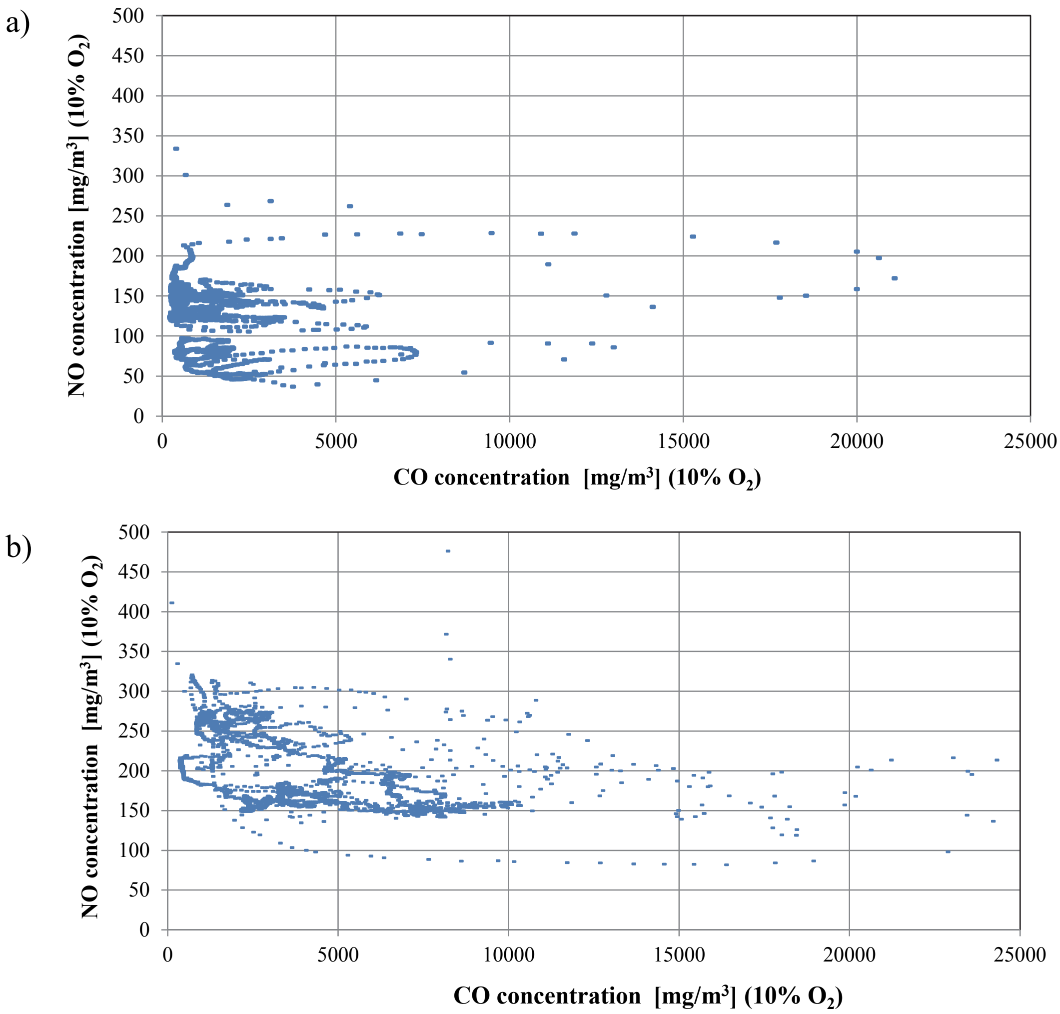

Fig. 5. Carbon monoxide concentration versus nitrogen oxide concentration in the flue gas; comparison between (a) the batch fired with high combustion air flow rate and (b) the batch fired at low combustion air flow rate

4. DISCUSSION

The results shown in Table 2 convey mean values of the measured parameters for batches fired at different air flow rates. It was observed that carbon monoxide and hydrocarbon emissions (calculated to CH_4) were higher in case of applying a lower air stream rate. It exceeded the limit value of 5000 mg/m^3 established in the Polish-European standard (PN-EN-303-5, 2012). For both batches relatively low boiler heat efficiency was observed, which results from incomplete combustion of fuel batch. During firing, oak logs were getting stuck and did not properly fall towards the nozzle as the lower logs got burnt out. This happens quite often while operating this type of boilers. Also the temperature in the nozzle, concentrations of nitric oxide and nitrogen oxides, boiler heat output, and heat efficiency were lower than in case of the higher air flow rate. Although the concentration of nitrogen oxides concentration NO_x for boilers with heat output of less than 0.5 MW is not regulated by law, it is of common agreement in Poland that it should not exceed 400 mg/m^3 (presented for 10% O_2 content in flue gas) (Kubica, 1999). As shown in Table 2, these concentrations are much lower in both batches.

It is commonly known that oxygen and temperature are important factors conditioning complete combustion. As observed in Figure 4, the temperature in the nozzle has a significant impact on carbon monoxide concentration value in both batches fired at different air flow rates. Carbon monoxide concentration decreases frequently as the temperature in the nozzle increases and vice versa.

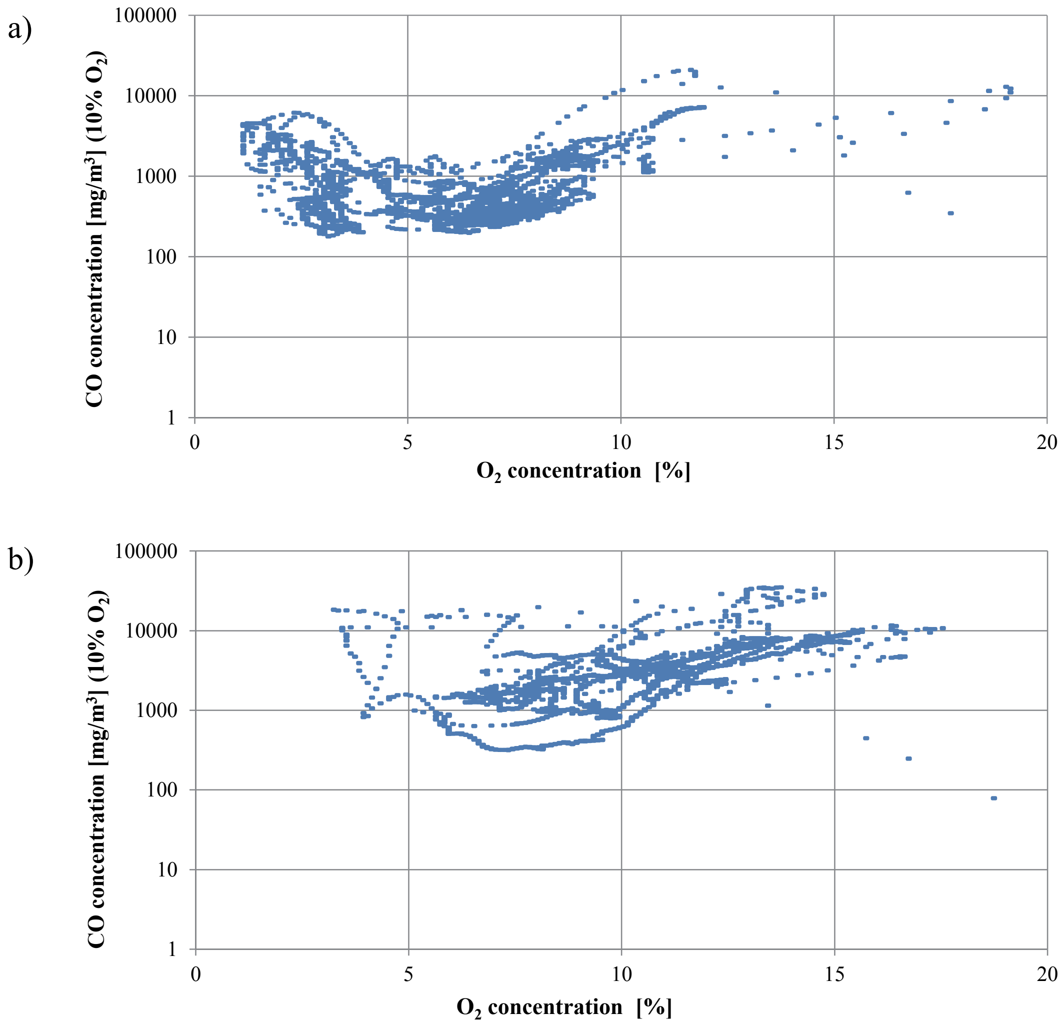

Fig. 6. Carbon monoxide concentration versus oxygen concentration in the flue gas; comparison between (a) the batch fired with high combustion air flow rate and (b) the batch fired at low combustion air flow rate

In terms of the correlation between oxygen concentration and the temperature in the nozzle analyzed in Fig. 4, it is clearly visible that, for both batches, as the temperature increases the oxygen concentration is reduced, the combusting process intensifies, while combustion air flow rate remains constant. However, the concentrations of carbon monoxide and hydrocarbons decrease with the increase of the temperature in the nozzle for both cases. The concentration variations of nitric oxide (and the concentration calculated to NO_x) depending on temperature changes differ for the batch burnt at lower and higher air flow ratio. This is related to the fact that, as commonly known nitric oxide concentration depends both on temperature and oxygen concentration. Usually, an increase in both oxygen concentration and temperature causes the rise of nitric oxide and nitrogen oxide concentration. In the presented study, these two factors intervene at the same time: oxygen concentration decreases and the temperature in the nozzle increases. In case of lower air flow ratio the influence of oxygen concentration on nitric oxide concentration seems to be predominant over the temperature's influence, therefore the nitric oxide concentration decreases with the temperature increase in the nozzle. In case of the higher air flow rate, however, as the temperature increases, nitric oxide concentration first is maintained at almost the same level and only then begins to increase. The influence of oxygen concentration resulting from intensive combustion is not predominant in this range.

As far as the correlation between carbon monoxide and nitric oxide concentration is concerned, it can be concluded based on Fig. 5 that nitric oxide concentration decreases as carbon monoxide concentration increases, equally for both batches and air flow rates. It was also observed that the hydrocarbon concentration increases as the carbon monoxide concentration increases. The correlations presented in Fig. 5 can then be explained by the influence of hydrocarbons on the nitric oxide (NO) reduction, according to the following reaction (Nowak et al., 2010):

$$2NO + 2C_nH_n + (2n + m/2 - 1)\, O_2 = N_2 + 2nCO_2 + mH_2O \qquad (1)$$

Finally, Fig. 6 shows the correlation between carbon monoxide concentration and oxygen concentration which provides important information on the oxygen concentration level at which carbon monoxide concentration presents the lowest values. It is an extremely relevant tool that helps to select the proper configuration of the oxygen lambda sensor, in case an automatic combustion air flow regulation system equipped with such lambda sensor was introduced to the boiler. Carbon monoxide concentration decreases as oxygen concentration increases until reaching a certain optimum value above which carbon monoxide concentration starts to increase for both batches (air flow rate settings). All the points visualized in Figs. 4 to 6 are values of parameter pairs measured at exactly the same time.

5. CONCLUSION

The experimental study presented above examined the process of oak log firing in an old type boiler - still commonly used in Poland - located in a full scale heat station with almost- real-life conditions, simulating domestic boiler operation.

Based on the results of the study it was concluded that combustion air stream rate has a significant influence on pollutant concentration level in the flue gas (mostly carbon monoxide and hydrocarbons). This justifies the desirability of installing an automatic air stream regulation system with an oxygen probe and regulating its settings according to the results of this study. Oxygen concentration would then have to be set to approx. 6-7%, which is the value found to be optimum for the studied type of boiler. Also, this study has shown that the position and shape of logs is of great importance for boosting boiler heat efficiency and overall combustion process - one needs to carefully select the shape of logs and their positioning in the gasification chamber, to make sure during firing they can easily and freely move downwards towards the nozzle. Also, wood log moisture is of importance to the reduction of pollutant concentration, it should be as low as possible.

The presented analytical method reflected in Figs. 4, 5, 6 can be used as a tool to assess the performance of other type of furnaces installed in low heat output boilers.

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