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CONCENTRATIONS OF CARBON MONOXIDE AND NITROGEN OXIDES FROM A 25 KW BOILER SUPPLIED PERIODICALLY AND CONTINUOUSLY WITH WOOD PELLETS

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The impact of the fuel feeding mode (continuous or periodic with different stand-by/operation time ratios) on carbon monoxide (CO) and nitrogen oxides (NO, NOx) concentration values in the flue gas was analysed for coniferous wood pellet firing. Experiments were performed in a 25 kW water boiler equipped with an over-fed wood pellet furnace located in a full scale heat station simulating real-life conditions. Influence of oxygen concentration and temperature in the combustion chamber on carbon monoxide and nitrogen oxide concentrations was presented in diagrams. Dust and hydrocarbon concentrations were also monitored. It was concluded that the commonly used periodic fuel supply does not necessarily cause a significant increase of carbon monoxide concentration, as compared to the continuous fuel feeding mode. Continuous fuel supply can even induce higher carbon monoxide concentrations when fuel mass stream is not chosen properly. Each time new fuel type is used in a specific furnace, one should perform experiments to determine the adequate settings (stand-by/operation time ratio, fuel mass streams, air stream) to obtain the optimal, lowest possible emission for a certain boiler heat output.

Keywords: coniferous, wood pellets, combustion, emission, heat station

1. INTRODUCTION

As this study examines low heat output heating boilers (<50 kW), typically used in domestic heat stations, it is important to notice that they, in comparison with high heat output boilers (>1MW), present a much higher 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 is only about 1% (Knaus, et al., 2000). These numbers have already changed as currently more modern boilers are being used in Germany. However, the figures depict the scale of the problem. In Poland probably, this proportion is similar or even higher, as customers more frequently use cheap boilers of simple and old design.

The reason behind it is mainly the fact that these boilers, in order to be limited in size and low-cost, are equipped with small combustion chambers. Their walls function directly as heat exchange surfaces and are reached by the flue gas much too fast. As a consequence, the flue gas is cooled and the combustion process is hampered. This problem is especially noticeable in case of biomass, as in the first stage of burning it releases as much as about 80 wt % of volatile organic compounds, contrary to hard coal with only about 20%, which makes the flue gas reach the cold heat exchange surfaces and be cooled even

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more quickly. Additionally, biomass is characterised by a lower heating value in comparison with hard coal, which results in a frequently lower temperature in the combustion chamber. All these factors create conditions that favor generation of considerable amounts of incomplete combustion products. Using wood pellets for residential heating enables the use of automated systems with higher burning efficiency and lower emission of incomplete combustion products as compared to wood log firing (Johanson, et al., 2004). Firing wood logs in heating boilers with low heat output requires manual operation and frequent opening of the combustion chamber which causes its cooling and as a consequence an increased concentration of incomplete combustion products in the flue gas. These boilers in most cases lack an automatic air stream regulation device equipped with an oxygen probe (lambda sensor) located downstream the boiler. Wood log boilers used currently in heat stations in Poland are one of the main sources of carbon monoxide emission (Juszczak, 2010, 2011). Pellets are therefore preferable to logs - while presenting a similar density they allow automated fuel supply (the combustion chamber does not need to be opened for feeding) which translates into higher temperature in the combustion chamber and therefore much lower carbon monoxide concentration as compared to wood log firing (Fiedler, 2004; Johansson et al., 2004). Over the last decade, wood pellets have become more popular and are often introduced to the heating boilers instead of wood logs (Boman, et al., 2003). They are especially common in Sweden, where they replaced fuel oil furnaces due to oil prices going up in the last decade. Also in Germany, Austria and recently in Poland one can notice a growing interest in wood pellet boilers. Limited availability of high quality and cheap wood pellets in Poland (that are currently used in power plants), aroused interest in agricultural biomass pellets as fuel for heating boilers with low heat output. Agricultural biomass has low ash melting temperature, which is why it should be fired at a temperature of less than 700°C (Werther et al., 2006), to avoid the production of slag that hampers furnace operation and combustion process . Also chlorine content is an important factor in biomass combustion as it can form KCl that melts at a low temperature. Therefore, it is recommendable to use additives such as Ca(OH)2 or dolomite that react with chlorine and impede KCl formation (Poskrobko et al., 2010, 2010, 2012). In wood pellet furnaces, an important factor that could influence pollutant emissions is the mode of automated pellet supply, namely: whether it is continuous or periodic, which is precisely the topic of this study. The majority of wood pellet furnaces with low heat output, even those produced by renowned manufacturers, do not enable stepless pellet stream adjustment. Instead, they use periodic fuel supply, which means that fuel stream is regulated manually by modifying the operation and stand-by time of the fixed-speed screw feeder, as well as the stream of air for combustion, to obtain the desired heat output of the boiler. The fact that air stream is constant during combustion process for the required boiler heat output and is not reduced during the stand-by period in pellet feeding lowers the temperature in the combustion chamber and substantially increases oxygen concentration, which results in an increase of carbon monoxide concentration. This is why continuous pellet feeding system would seem to be much more beneficial. Nevertheless, it is rarely introduced as a technical solution in low heat output heating boilers with wood pellet furnaces due to its high cost.

For periodic and continuous fuel supply systems described above, settings would differ depending on wood type. Furnace producers do suggest recommended settings (operation time, stand-by time, air stream). However they do so only for good quality 100% deciduous wood pellets as deciduous wood is considered to be the best biomass type for firing due to its low nitrogen (0.1-0.2 %), ash (1%) and sulfur content (negligible). These settings are not always adequate for coniferous or mixed wood pellets. Coniferous wood due to high resin content burns faster and more intensively than deciduous wood. Therefore, it would seem necessary to conduct studies to determine the most beneficial settings for periodic supply of coniferous wood pellets for which carbon monoxide concentration is the lowest. Using that opportunity, it would be worth verifying if continuous supply of pellets to the furnace markedly reduces carbon monoxide concentration.

The most useful and easily controllable pollutant emission indicator is carbon monoxide concentration (Johanson et al., 2004). The Polish-European law (PN-EN 303-5, 2004) is quite liberal in that aspect as it allows carbon monoxide concentration of even 3000 mg/m^3 for heating boilers with a heating output of less that 300 kW. However, internal legislation of some countries, e.g. Sweden, limits the permitted CO concentration to 2000 mg/m^3. The criteria are even stricter in order for a boiler to be granted an ecological certificate. For example, to obtain the Nordic countries' Svan Mark certificate it cannot exceed 1000 mg/m^3 and for the German Blauer Engel certificate it needs to be lower than 100 mg/m^3 (Fiedler, 2004). Obviously, to reach these values one needs to use high quality deciduous wood pellets with no contamination, such as sand or sillicates. The most modern wood pellet furnaces equipped with the oxygen probe and continuous fuel supply provide carbon monoxide concentrations as low as 10 - 50 mg/m^3 (Olsson, et al, 2006). These values, however, can only be reached in stable laboratory conditions, with a high heat output, and definitely not over a longer period of time in a real-life heat station during operation. For a heat station with conditions resembling the real ones (periodic fuel supply, no oxygen probe for air stream regulation) concentrations vary from 300 to 800 mg/m^3 (Boman et al., 2011; Fiedler et al., 2007; Juszczak, 2011; Kjallstrand et al., 2004; Olsson et al., 2004; Verma et al., 2011). Also other parameters are monitored, the most important ones being concentrations of ash and nitrogen oxides. Polish environmental legislation (PN-EN 303-5, 2004) defines the permitted value of ash concentration in the flue gas at 150 mg/m^3. Although it does not specify the permitted value for nitrogen oxide concentrations, producers of small heating boilers must comply with NOx concentration below 400 mg/m^3, to obtain the Polish ecological certificate (Kubica, 1999), which facilitates boiler commercialisation. By comparison, the criteria of the German Blauer Engel certificate are: NOx below 150 mg/m^3, ash below 30 mg/m^3. All concentrations are presented for 10% O_2 content in flue gas.

2. AIM OF STUDY

The experimental study presented below examines the emission of pollutants during coniferous wood pellet firing in a low heat output boiler working in almost real-life conditions. The aim of the experimental study was to determine:

- whether the emission of carbon monoxide is much higher for periodic wood pellet supply than that for continuous fuel supply,
- at which value of oxygen concentration one can achieve the lowest possible carbon monoxide concentration (a parameter which is necessary to determine the adequate air stream for combustion, especially if oxygen probe is to be used in the future),
- the fluctuations of nitrogen oxides and carbon monoxide concentration depending on the temperature in the combustion chamber while the oxygen concentration is changing,
- the fluctuations of nitrogen oxides and carbon monoxide concentration depending on oxygen concentration while the temperature in the combustion chamber is changing.

3. MATERIAL

The study was performed using „ECOPELLET" wood pellets supplied by the Polish company Barlinek. Dimensions: diameter 6 mm, length up to 40 mm, made entirely (100%) from coniferous wood sawdust. Technical pellet parameters indicated by the producer: moisture 10%, ash content 0.7%, lower heating value 18.5 MJ/kg, nitrogen content 0.35%. „ECOPELLET" product is certified to meet the highest European quality standard DIN plus no. 7A105, corresponding with the recent European standard E DIN EN 14961-2:2010-07. Pellet lower heating value was verified in our laboratory using the calorimetric method.

4. EXPERIMENTAL SET UP

A schematic layout of the experimental set-up is shown in Figure 2. The experiments were carried out in a full scale heat station (Fig. 1) equipped with a 25 kW boiler with an over-fed wood pellet furnace. The heat station belongs to Institute of Environmental Engineering of Poznan University of Technology and has been prepared for investigations.

Unlike many studies performed by accredited laboratories that examine boilers in idealised conditions, this study pays special attention to provide conditions as similar to the real ones as possible and therefore simulate domestic boiler operation where heat demand is variable. To achieve that, heat accumulated in the water heat storage of the heat station was transferred to radiators and water heat storage in the small detached house through insulated underground pipelines, when necessary, to the atmosphere with a fan-coil with regulated heat output, located on the roof of the heat station.

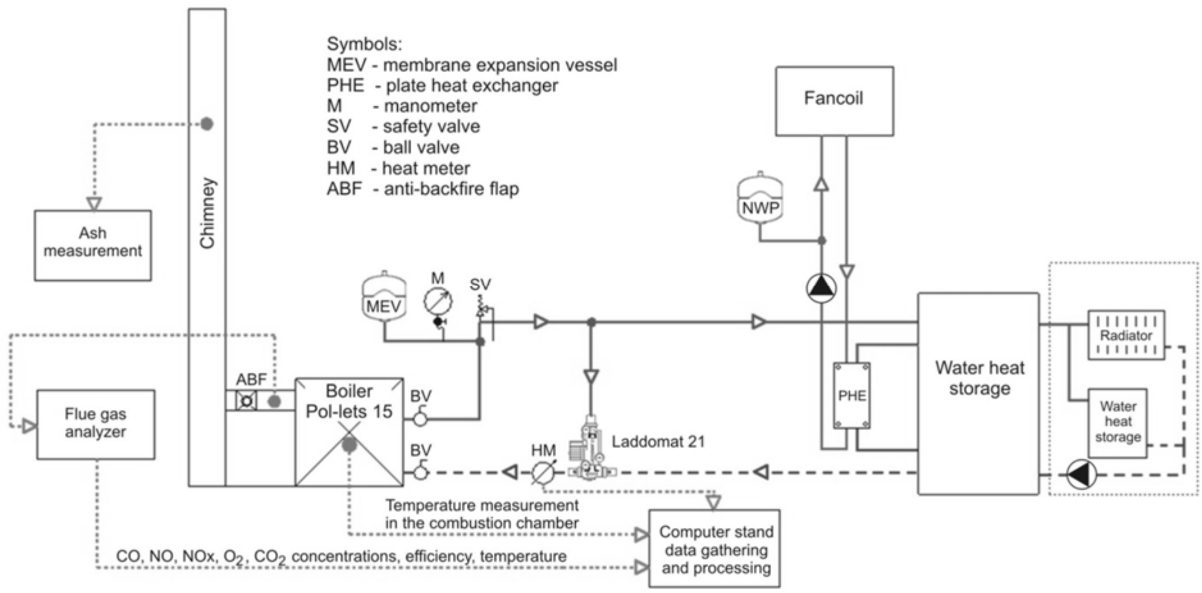

Fig. 1. Schematic layout of the experimental set-up – biomass fed heat station and heat receivers

The boiler lacks an automatic device with an oxygen probe (lambda sensor) that would measure oxygen concentration in the flue gas downstream the boiler. Air stream is modified manually by fan speed regulation, ranging from 10 to 100% of its maximum value. Pellets are supplied from the storage to the furnace by means of a fixed-speed screw feeder. The furnace contains a horizontal fixed-speed screw pellet dispenser that subsequently introduces pellets to the burning region. The furnace is equipped with an electric ignition device. Originally the boiler works with periodic pellet supply system. However, in this study a continuous pellet supply system was arranged by installing an inverter that enforced stepless adjustment of screw feeder resolutions.

The boiler is connected to a 900 l water heat storage through a special mixing and pumping device, Laddomat 21 (Fig.1), composed of a pump and three thermal valves that open or close automatically depending on incoming water temperature. This device enables water flow in the boiler only after it reaches the temperature of 64°C. Then, water begins to flow in short circuit through the boiler and the mixing and piping device only and after reaching the temperature of 72ºC it also flows through the water heat storage of the heat station. The water temperature at the inlet of the boiler is always maintained over 64°C in order to keep the combustion chamber walls hot and therefore minimise pollutant emission.

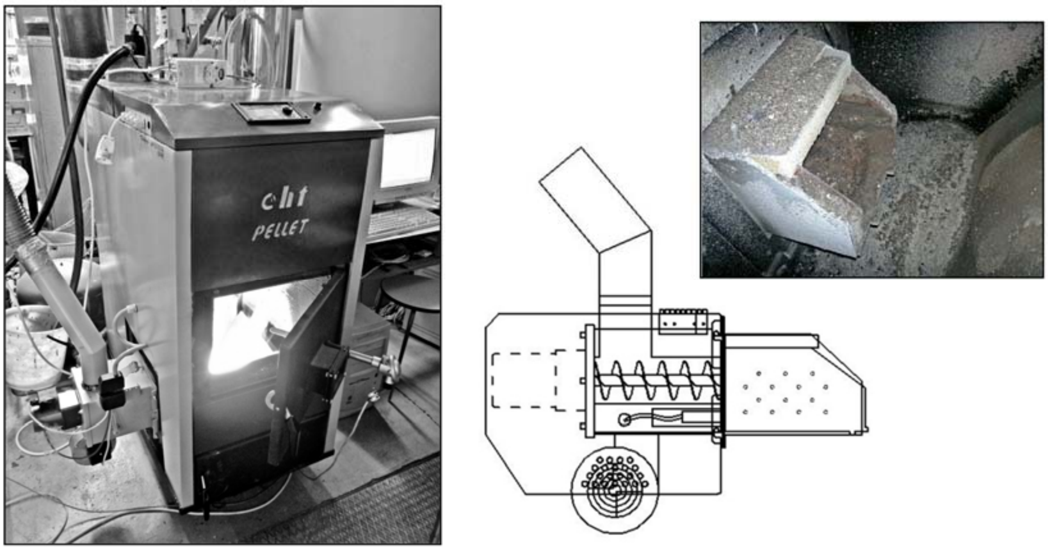

Fig. 2. 20 kW pellet supplied boiler during experiments with open door of combustion chamber for demonstration, thermocouple installed on the furnace door, scheme and view of the over- fed furnace

4.1. Experimental procedure and measuring equipment

The study examined pollutant concentrations for different fuel streams (3.0, 4.5 and 6.0 kg/h) and for each fuel stream for six different fuel feeding modes (five periodic and one continuous mode). Each of the six different feeding methods was performed without interruption for 5 hours. Experimental design is shown in Table 1. For fuel stream of 3.0 kg/h the operation/stand-by time ratio is 2:3, for 4.5 kg/h 2:1 and for 6.0 kg/h 8:1. These settings were selected to obtain good furnace operation. The speed of the screw feeder was constant for every fuel feeding mode of the fuel stream. The speed for each fuel stream was different.

Air stream was chosen empirically to obtain the lowest possible CO concentration while observing gas analyzer indications in terms of carbon monoxide concentrations and watching the flame in the combustion chamber through a sight glass. For the fuel streams of 3.0, 4.5 and 6.0 kg/h air stream value was set at about 30, 50 and 100% of its maximum, respectively.

Gas pollutant concentrations in the flue gas downstream the boiler as well as flue gas temperature were measured using Vario Plus (MRU) flue gas analyser (Germany). The flue gas analyzer also calculated boiler chimney loss. Oxygen (O_2), nitric oxide (NO), nitrogen dioxide (NO_2) concentrations were measured with electrochemical cells. Gas analyser calculated NO_x concentration as a total of NO (transformed to NO_2) and NO_2 concentration. CO and C_xH_y concentrations were measured using the infrared procedure. Temperature in the combustion chamber was measured about 0.30 m above the flame with a radiation shielded thermocouple PtRhPt. The measurements of temperature in the flame made with a pyrometer showed that the temperature measured with the thermocouple was about 200°C lower than the temperature in the flame (unfortunately there were no technical possibilities of taking flue gas samples from the flame area for temperature measurement and the boiler producer did not allow structural changes in the boiler that would make taking flue gas samples from the flame area possible). Dust concentration in the chimney was measured using a gravimetric dust meter equipped with isokinetic aspiration.

Heat received by the boiler water and boiler heat output were measured with an ultrasonic heat meter. Fuel stream was measured using a Sartorius lab balance. Pellet lower heating value was measured using the calorimetric method and 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 based on measured chimney loss and other estimated heat losses. Gas concentrations, heat output and temperature were measured continuously and transmitted in real time to a personal computer where they were registered every 2 seconds, mean values were calculated every 10 seconds and analysed in diagrams. The mean values were calculated as arithmetic average. For gas pollutant concentrations (CO, NO, NO_x), uncertainty intervals were calculated for a 95% confidence level (Tab. 1).

5. RESULTS

The results obtained during the measurements performed in the heat station are presented below. Mean parameter values for different fuel supply methods are presented in Table 1 and visualised/compared in Figure 3. Uncertainty intervals of the parameters (with a 0.95 probability) were calculated and presented in Table 1. In Figure 4 pollutant concentrations and other measurement parameters versus time for 3 kg/h continuous fuel supply and 3 kg/h periodic fuel supply: operation time 60s, stand-by time 90s were compared. Figures 5-7 show CO and NO, NO_x concentrations versus temperature in the combustion chamber and oxygen concentration in the flue gas for 3.0 and 6.0 kg/h continuous fuel feeding and one periodic feeding mode for fuel stream 3.0 kg/h. Rough measurements of dust concentration showed the values between 30 and 50 mg/m^3. All pollutant concentrations are presented for 10% O_2 content in flue gas.

The values of uncertainty intervals for CO, NO, NO_x concentrations indicate the magnitude of fluctuations of these parameters for a certain fuel feeding method.

Table 1. Mean parameter values measured for all different fuel feeding methods

			Pollutant concentration							
Fuel mass stream air stream	Fuel feeding mode	Operation: stand-by	CO	NO	NO_x	Temp. in combustion chamber*	O_2 conc.	Air excess ratio	Heat output	Heat Efficiency
[kg/h], %**	[-]	[s]	[mg/m^3] for 10% O_2 content in flue gas			[°C]	[%]	[-]	[kW]	[%]
3.0, 30	continuous		342 ±52	270 ±17	416 ±27	479	10	1.8	13.1	85
	periodic	20:30	180 ±6	296 ±9	458 ±14	543	9	1.7	13.1	85
		30:45	330 ±37	242 ±22	373 ±36	521	9	1.7	13.1	85
		40:60	612 ±71	226 ±0	349 ±1	493	11	2.0	13.0	84
		50:75	1707 ±672	215 ±4	330 ±8	496	11	2.0	12.6	82
		60:90	1543 ±83	201 ±10	308 ±15	501	10	1.8	12.8	83
4.5, 50	continuous		1060 ±108	306 ±35	473 ±54	565	8	1.6	19.4	84
	periodic	20:10	2173 ±348	263 ±37	405 ±58	658	5	1.3	19.7	85
		30:15	933 ±178	227 ±34	348 ±53	661	5	1.3	19.2	83
		40:20	3806 ±633	249 ±38	318 ±5	548	9	1.9	19.1	83
		50:25	325 ±5	286 ±4	442 ±6	603	8	1.6	19.2	83
		60:30	1182 ±44	267 ±20	411 ±33	631	6	1.4	19.1	83
6.0, 100	continuous		261 ±25	305 ±14	471 ±22	603	8	1.6	25.3	82
	periodic	40:5	477 ±154	247 ±5	381 ±8	693	5	1.3	25.6	83
		80:10	551 ±287	248 ±13	382 ±20	667	5	1.3	25.6	83
		120:15	2488 ±384	269 ±13	414 ±18	634	6	2.0	24.9	81
		160:20	798 ±428	283 ±18	436 ±28	676	5	1.4	25.5	83
		200:25	603 ±267	288 ±3	445 ±4	684	5	1.4	25.6	83

*Temperature in the combustion chamber (controlled with a thermocouple) is about 200°C lower than the temperature in the flame

**Percent of maximum value of fan rotation

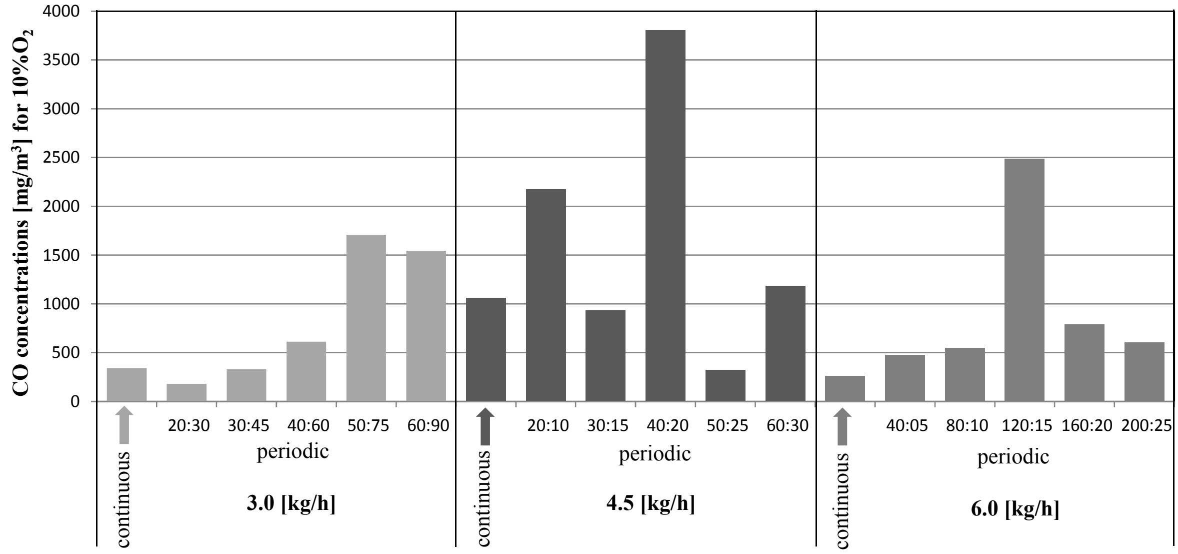

Fig. 3. Comparison of CO concentrations in correlation with fuel mass stream and fuel feeding mode, according to Table 1

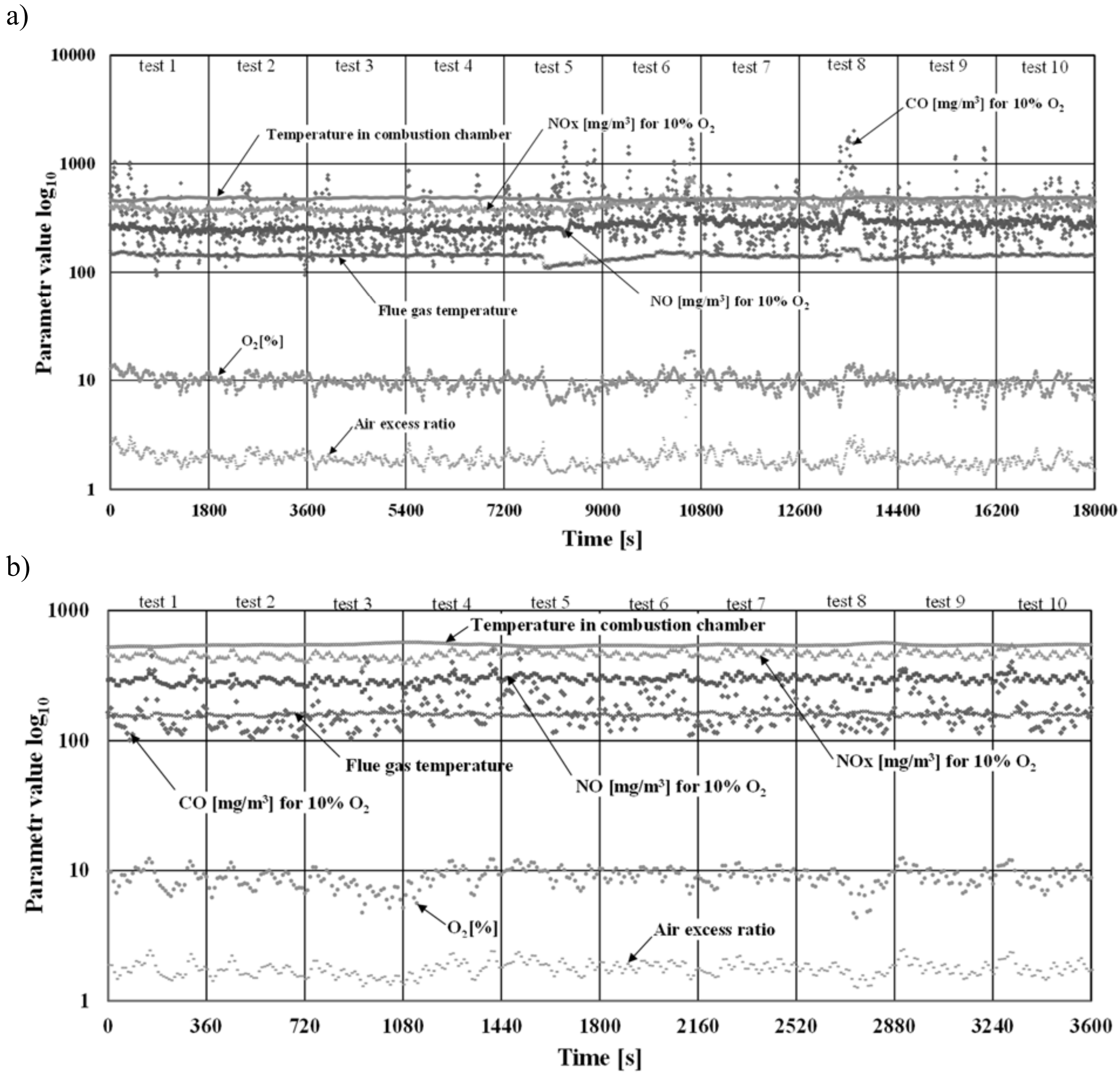

Fig. 4. Pollutant concentrations and other measurement parameters versus time for 3 kg/h continuous fuel supply (a) and 3 kg/h, periodic fuel supply: operation time 60s, stand-by time 90s (b)

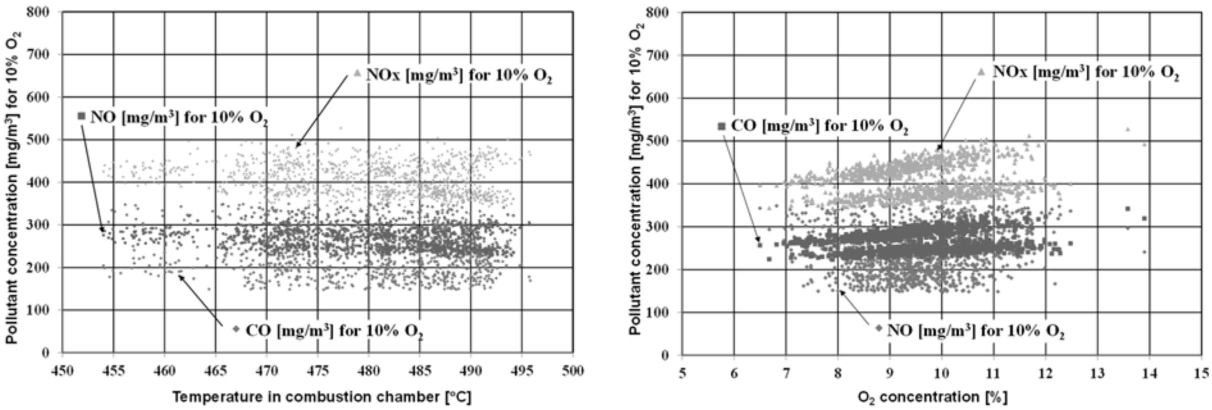

Fig. 5. CO and NO, NO_x concentrations versus temperature in the combustion chamber (left) and oxygen concentration in the flue gas (right) for continuous fuel feeding and fuel mass stream of 3 kg/h

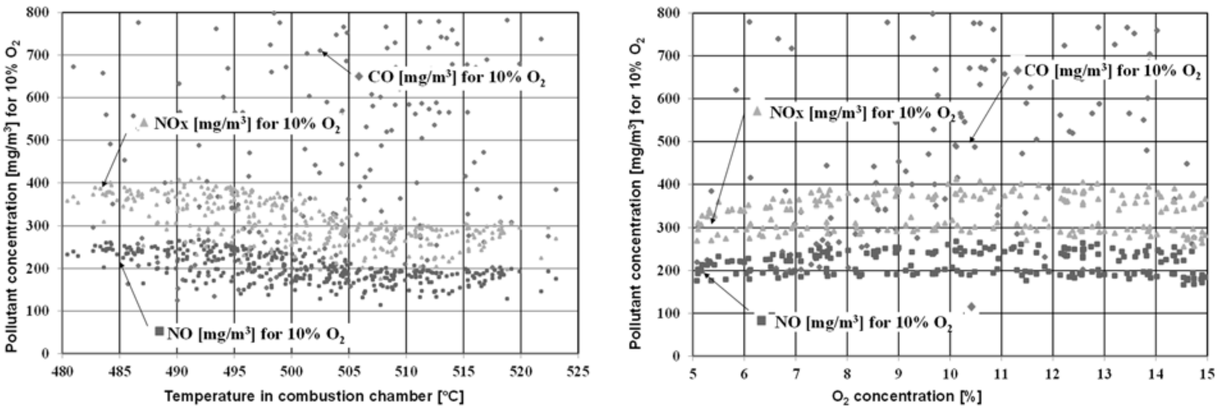

Fig. 6. CO and NO, NO_x concentrations versus temperature in the combustion chamber (left) and oxygen concentration in the flue gas (right) for fuel mass stream 3 kg/h and periodic fuel supply: operation time 60 s, stand-by time 90s

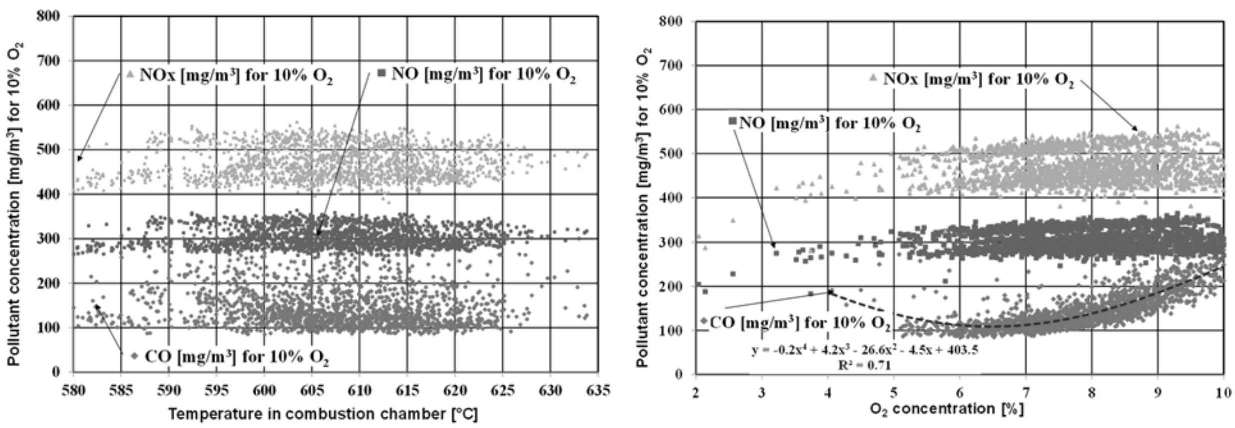

Fig. 7. CO and NO, NO_x concentrations versus temperature in the combustion chamber (left) and oxygen concentration in the flue gas (right) for continuous fuel feeding and fuel mass stream of 6 kg/h

6. DISCUSSION

Although it would seem that carbon monoxide concentration for continuous fuel supply mode should be lower than that for periodic mode, it was not always the case (see Table 1, Fig. 3). Continuous fuel feeding was only more favorable at the highest fuel mass stream (6 kg/h) when the temperature in the combustion chamber was above 600°C (corresponding to 800°C in the flame area in the furnace).

For fuel streams of 3 and 4.5 kg/h, the temperature in the combustion chamber was low and in case of continuous feeding mode most probably the pellets were not completely fired, which is why carbon monoxide concentration was high. Table 1 shows that the increase of stand-by period is not always accompanied by an increase of carbon monoxide concentration. In order to lower carbon monoxide emission the value of air stream for combustion needs to be adjusted as well.

Sometimes, it can be clearly seen that CO concentration decreases with the oxygen concentration increase till a certain minimum value, after which CO concentration starts to decrease (Figure 7). Determining oxygen concentration for which carbon monoxide concentration is the lowest might be helpful in case an automatic air stream regulation oxygen probe downstream the boiler is installed in the future.

In the studied furnace, in case of periodic fuel supply it can be assumed that an increase of CO concentration above the minimum value is caused also by a substantial reduction of temperature in the combustion chamber during the stand-by in pellet supply.

Nitrogen oxide (NO and NO_x) levels depend mainly on the amount of nitrogen introduced into the furnace. As coniferous wood (the studied material) presents higher nitrogen content than deciduous wood, these concentrations were significant and varied from 201 (NO) and 308 (NO_x) mg/m^3 to 306 (NO) and 473 (NO_x) mg/m^3 (at the temperature in the furnace below 900°C), Table 1. A slight increase of nitrogen oxide (NO and NO_x) levels was observed when oxygen concentration increased and a subtle decrease when temperature in the combustion chamber increased. This means probably that at the same time when temperature in combustion chamber increased combustion process was more intensive and oxygen concentration decreased. For all the cases presented in Table 1 for an almost-real life conditions a relatively high boiler heat efficiency of above 80 % was obtained.

Throughout the experiments, the presence of hydrocarbons in the flue gas was not detected, whereas soot was observed in the damper. This could mean that the combustion process was being partially hampered on the cool surfaces of the relatively small combustion chamber in spite of applying the Laddomat 21 mixing and pumping device (Fig.1). Dust concentrations of 30÷50 mg/m^3 were much below the officially permitted values of 150 mg/m^3 (PN-EN 303-5, 2004).

7. CONCLUSION

Based on the results of this study it can be concluded that applying periodic fuel supply instead of continuous feeding mode is not necessarily accompanied by a radical increase in carbon monoxide concentration. Actually, the study has shown that in some conditions it was quite the opposite and CO concentrations were lower for periodic fuel supply. Therefore, the introduction of a continuous pellet feeding system as a theoretically a superior system is not justified as far as the studied over-fed furnace and wood type is concerned, as it considerably increases the selling price of the boiler.

Generally speaking, to keep CO concentration levels low one has to carefully select settings: fuel mass stream and air stream for both fuel feeding modes and additionally stand-by/operation time ratio for periodic fuel supply. As boiler producers only recommend settings for pure deciduous wood pellets, in case of coniferous or mixed wood pellets or any other new kind of fuel these settings need to be determined experimentally for a specific boiler and furnace type.

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