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COMPARISON OF CO AND NO_x CONCENTRATIONS FROM A 20 kW BOILER FOR PERIODIC AND CONSTANT WOOD PELLET SUPPLY

The impact of the fuel feeding mode (continuous or periodic with various stand-by/operation time ratios) on carbon monoxide (CO) and nitrogen oxides (NO, NO_x) concentration values in the flue gas was analyzed for coniferous wood pellet firing. Experiments were performed using a 20 kW water boiler equipped with an under-fed (retort) wood pellet furnace located in a full scale heat station simulating real-life conditions. Impact of oxygen concentration and temperature in the combustion chamber on the concentrations of carbon monoxide and nitrogen oxide have been examined. It was concluded that the commonly used periodic fuel supply does not necessarily cause an important increase of the concentrations of carbon monoxide compared to those in the continuous fuel feeding mode. Continuous fuel supply can even imply higher concentrations of carbon monoxide when fuel and air streams are not chosen properly.

1. INTRODUCTION

Low heat output heating boilers (<50 kW), typically used in domestic heat stations, in comparison with high heat output boilers (>1 MW), 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 the year 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 about 1% [1]. These numbers have already changed as currently more modern boilers are being used in Germany, it depicts however the scale of the problem. In Poland, this

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proportion is probably similar or even higher, as customers more frequently use cheap boilers of simple and old design.

The reason behind it is mostly 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 visible in the case of biomass, as in the first stage of burning it releases as much as 80 wt. % of volatile substances, as opposed to hard coal where it is only 20 wt. %, which makes the flue gas reach the cold heat exchange surfaces and be cooled even quicker. Additionally, biomass is characterized by a smaller lower heating value in comparison with hard coal which leads frequently to a lower temperature in the combustion chamber. All these factors create conditions that favor generation of considerable amounts of incomplete combustion products.

The most useful and easily controllable pollutant emission indicator for incomplete combustion products is CO concentration. The Polish-European law [2] is quite liberal in that aspect as it permits the CO concentration to be even 3000 mg/m^3 for high heat efficiency heating boilers with a heating output of less than 300 kW. However, internal legislation of some countries, e.g. Sweden, limit 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 Bauer Engel certificate it needs to be lower than 100 mg/m^3 [3]. Obviously, to reach these values one needs to use high quality deciduous wood pellets with no contamination, such as sand or silicates. The most modern wood pellet furnaces equipped with the oxygen probe and continuous fuel supply can give as low CO concentrations as 10–50 mg/m^3 [4]. These values, however, can only be reached probably 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. In the case of a heat station with conditions resembling the real ones (periodic fuel supply, no oxygen probe air stream regulation) the concentrations vary from 300 to 800 mg/m^3 [5–8]. It does not specify the permitted value for nitrogen oxide concentrations, however, producers of small heating boilers must comply with NO_x concentration of below 400 mg/m^3, in order to obtain the Polish ecological certificate [10], which facilitates boiler commercialization. All concentrations are presented for 10% O_2 content in flue gas.

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 is described by low ash melting temperature which is why it should be fired at a temperature lower than 700 °C [11], in order to avoid the production of slag that hampers furnace operation and the combustion process. Also chlorine content is an important factor in biomass combustion as chlorine can form KCl melting at a low temperature. Therefore, it is recommended to use additives such as $Ca(OH)_2$ or dolomite that react with chlorine and impede KCl formation [12–14]. Interesting results of study in the area of pollutant emission from firing biomass and other fuels can be found in the papers by Musialik--Piotrowska et al. [15, 16] and Hardy et al. [17].

An important factor that could influence pollutant emissions of wood pellet furnaces 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 fluent pellet stream regulation. 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 in the beginning of firing process, in order to obtain the desired heat output of the boiler. The fact that air stream is constant for the required boiler heat output and is not reduced during the stand-by period in pellet feeding causes lowering of the temperature in the combustion chamber and excessive increase of oxygen concentration, and as a result an increase of CO concentration. This is why continuous pellet feeding system would seem to be much more beneficial. Nevertheless it is barely introduced as a technical solution in low heat output heating boilers with wood pellet furnaces due to its elevated cost. For periodic fuel supply systems described above, the settings would differ depending on wood type. Furnace producers do suggest recommended settings (operation time, stand-by time, air stream), however 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 negligible sulfur content. These settings are not always adequate for coniferous or mixed wood pellets.

2. EXPERIMENTAL SET UP AND PROCEDURE, MEASURING EQUIPMENT, MATERIAL

In the experimental study, the emission of pollutants has been examined during coniferous wood pellet firing in a low heat output boiler with under-fed furnace. The aim of performed experimental study was to determine:

- whether the concentration of CO is much higher for periodic wood pellet supply than for continuous fuel supply,
- at which value of oxygen concentration one can achieve the lowest possible CO 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 concentrations of nitrogen oxides and carbon monoxide depending on the temperature and oxygen concentration in the combustion chamber upon changing one of these parameters,

The experiments were carried out in a full scale heat station equipped with a 20 kW boiler with an under-fed wood pellet furnace (Fig. 1). Unlike many studies performed by accredited laboratories that examine boilers in idealized conditions, in this study, a special attention was paid to ensure conditions similar to the real ones and therefore simulate domestic boiler operation where heat demand is variable. The boiler lacked an automatic device of air stream with an oxygen probe (lambda sensor) in the flue gas downstream the boiler. Air stream was modified manually at the beginning of the firing process by fan speed regulation, ranging from 10 to 100% of its maximum value. Pellets were supplied from the storage to the furnace by means of a fixed-speed screw feeder. The furnace contained a horizontal fixed-speed screw pellet dispenser that subsequently introduced pellets to the burning region. The furnace was equipped with an electric ignition device.

Fig. 1. A view of 20 kW pellet supplied boiler (Biomax, Lumo type, Poland) (left), and under-fed (retort) furnace (Bioline 20, Ecotec type, Sweden) (right)

Originally the boiler worked with a periodic pellet supply system. However, for the purpose of this study, a continuous pellet supply system was arranged by installing an inverter that enforced fluent regulation of screw feeder resolutions. The boiler was connected to a 900 dm^3 water heat storage through a special mixing and pumping device, Laddomat 21 (Swedish production) composed with a pump and three thermal valves that open or close automatically depending on incoming water temperature. This device enabled water flow in the boiler after the temperature of 64 °C was reached. The water at the inlet of the boiler was maintained at temperature over 64 °C in order to keep the combustion chamber walls hot and therefore minimize emission of incomplete combustion products.

The gas pollutant concentrations in the flue gas downstream the boiler as well as the flue gas temperature were measured using a Vario Plus (MRU) flue gas analyzer (Germany). Concentrations of O_2, NO, and NO_2 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 infrared radiation. The flue gas analyser also calculated chimney loss. Temperature in the combustion chamber was measured ca. 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 is about 250 °C lower than the temperature in the flame. Unfortunately, it was not possible to make structural changes in the boiler to take flue gas samples directly from the flame area. 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 efficiencies calculated based on chimney loss and other estimated heat losses.

The study was performed using “Ecopellet” wood pellets certified to the highest European quality standard DIN plus no. 7A105, corresponding with the recent European standard E DIN EN 14961-2:2010-07, ordered from the Polish Company Barlinek. The pellets 6 mm in diameter, up to 40 mm long, were made entirely from coniferous wood sawdust. Their moisture was 10%, ash content 0.7%, lower heating value 18.5 MJ/kg, nitrogen content 0.35%.

In the study, pollutant concentrations were examined for three different fuel streams (3.0, 4.5 and 6.0 kg/h) and related three different speeds of screw pellet dispenser. For each fuel stream, six different fuel feeding modes (five periodic and one continuous mode) were applied. Each of the feeding modes was performed for 5 continuous hours. Experimental design is presented in Table 1. For fuel stream of 3.0 kg/h, the operation/stand-by time ratio was 2:3, for 4.5 kg/h 2:1 and for 6.0 kg/h 8:1. Such settings result from the necessity of obtaining good furnace operation. Air stream was chosen empirically in order to obtain the lowest possible CO concentration while observing gas analyzer indications in terms of CO concentrations and watching the flame in the combustion chamber through a sight glass. For the examined fuel streams of 3.0 , 4.5 and 6.0 kg/h, the air stream values were set at about 30, 50 and 100% of their maximum, respectively. Gas pollutant concentrations, temperature in combustion chamber and oxygen concentration were measured continuously and transmitted in real time to a personal computer where they got recorded every 2 s, mean values were calculated every 10 s and analyzed on diagrams (Figs. 3–8). For gas pollutant concentrations (CO, NO, NO_x), uncertainty intervals were calculated with a 0.95 probability (Table 1).

Table 1. Mean parameter values measured for all fuel feeding modes

Fuel mass stream [kg/h]	Fuel feeding mode	Time of operation: stand-by mode [s]	Pollutant concentrations for 10% O_2 in flue gas [mg/m^3]			Temperature in combustion chamber[a] [°C]	O_2 concentration [%]	Air excess ratio	Heat output [kW]	Heat efficiency [%]
			CO	NO	NO_x					
3.0	continuous		443±32	290±17	446±27	461	9	1.8	12.6	82
	periodic	20:30	236±26	242±9	373±14	482	8	1.6	13.0	84
		30:45	418±33	257±22	395±36	425	8	1.6	13.3	86
		40:60	246±28	239±10	369±16	462	8	1.6	12.8	83
		50:75	266±22	273±4	425±8	447	9.5	1.8	12.7	85
		60:90	284±36	285±10	445±15	430	9	1,9	13.1	84
4.5	continuous		329±49	313±35	423±54	440	10	1.9	19.2	83
	periodic	20:10	310±34	272±37	423±58	437	10	1.9	19.0	82
		30:15	237±28	247±34	382±53	462	7	1.5	19.2	83
		40:20	231±31	254±38	391±5	455	7	1.5	19.2	83
		50:25	299±41	256±4	394±6	436	7	1.5	19.2	83
		60:30	350±39	240±20	369±33	437	7	1.5	19.7	85
6.0	continuous		392±46	241±14	371±22	431	7.5	1,6	26.5	86
	periodic	40:5	302±44	267±5	415±8	463	8	1.6	25.9	84
		80:10	293±67	279±13	432±20	459	7.5	1.6	25.6	83
		120:15	329±38	281±13	435±18	433	7.5	1.6	25.3	82
		160:20	335±28	282±18	437±28	439	9.5	1.8	25.0	81
		200:25	347±26	254±3	392±5	437	7.5	1.6	25.6	83

[a]Temperature in the combustion chamber (measured with a thermocouple) is ca. 250 °C lower than the temperature in the flame (measured with a pyrometer).

3. RESULTS AND DISSCUSION

Figures 2, 3, 5, 7 present time dependences of gas pollutant concentrations and of other parameters. All of them seem to display a similar shape. Figures 4, 6, 8 show dependences of CO, NO and NO_x concentrations on temperature in the combustion chamber and on oxygen concentration in the flue gas for 3 kg/h continuous fuel feeding and some periodic feeding modes.

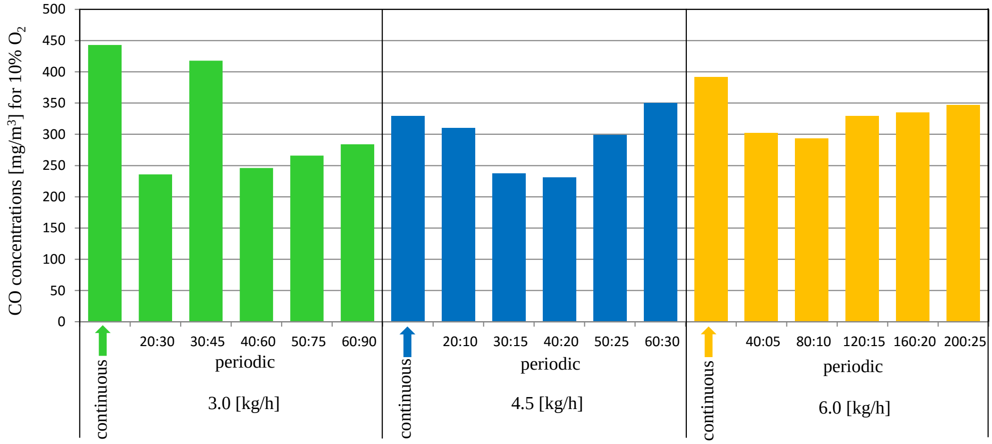

Fig. 2. CO concentrations in correlation with fuel mass stream
and fuel feeding mode, according to Table 1

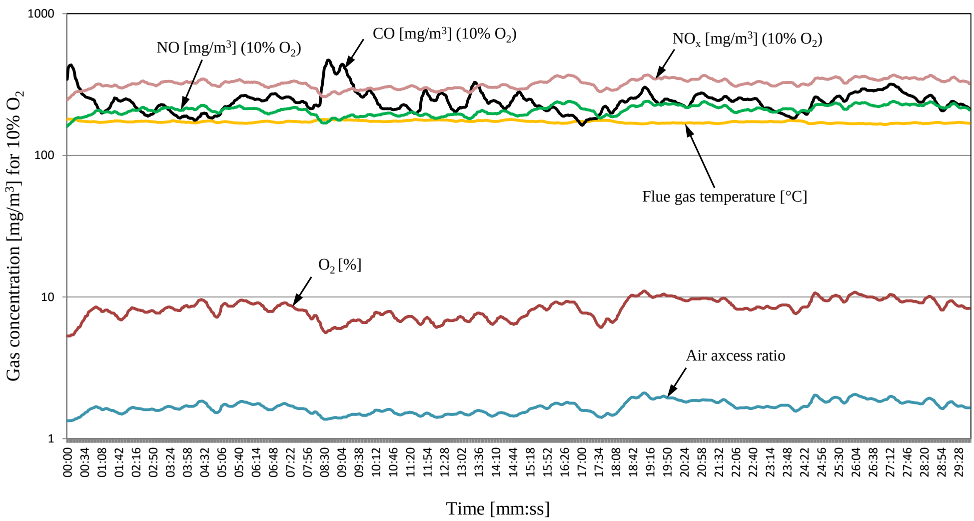

Fig. 3. Time dependences of pollutant concentrations
and other parameters for 3 kg/h continuous fuel supply

Correlations obtained for other fuel feedings were similar to those presented in the paper. Rough measurements of dust concentration showed the values between 30 and 50 mg/m^3. All pollutant concentrations were calculated 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.

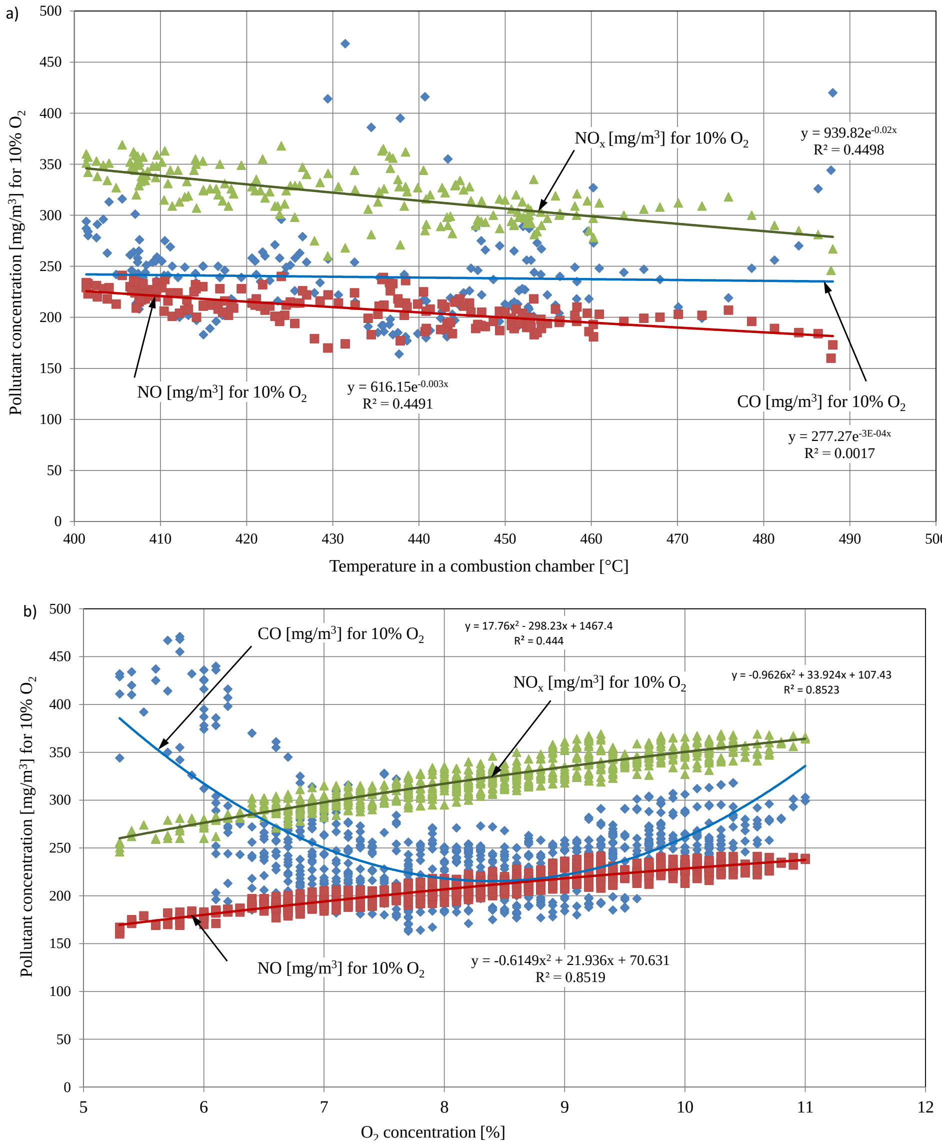

Fig. 4. Dependences of CO and NO, NO_x concentrations on temperature in the combustion chamber (a), and on oxygen concentration in the flue gas (b) for continuous fuel feeding and fuel mass stream of 3.0 kg/h

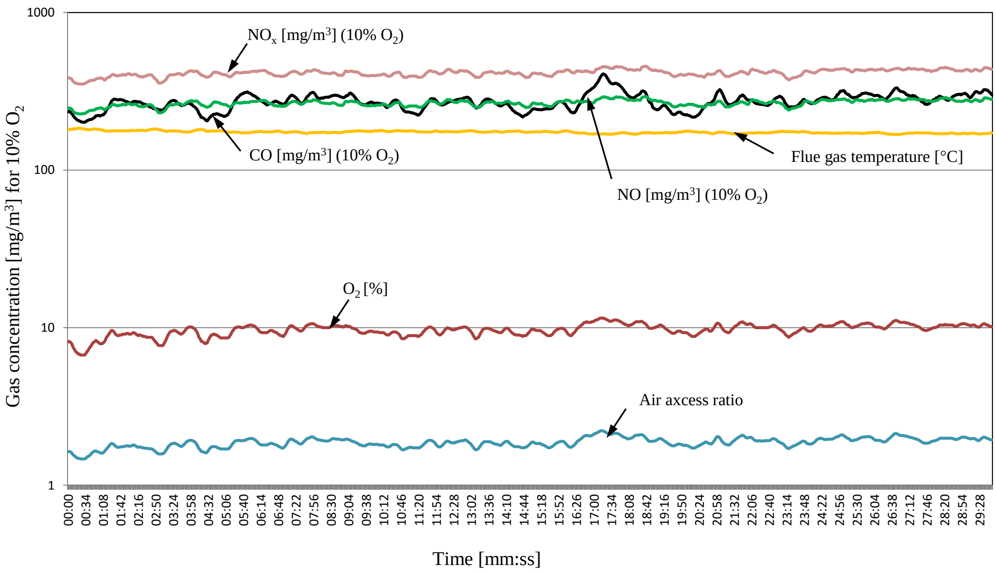

Fig. 5. Time dependences of pollutant concentrations and other parameters for 3 kg/h periodic fuel supply: operation time 20 s

CO concentrations measured during all tests were below 450 mg/m^3 (Table 1). Although it would seem that CO concentrations for continuous fuel supply mode should be lower than those for periodic mode, it was quite the opposite for most cases (Table 1). The highest value of CO concentration was measured for 3 kg/h continuous supply, probably due to too low air stream. Combustion in all cases was performed at low temperatures, and during continuous feeding most probably the pellets had not enough time to be completely fired and CO concentration was relatively high. Table 1 and Fig. 2 show that the increase of stand-by period is not always accompanied by an increase of CO concentration. In order to decrease CO concentration, the air stream for combustion needs to be adjusted as well. However, CO concentration decreases upon increasing oxygen concentration to a certain minimum value, after which CO concentration starts to decrease (Figs. 4, 6, 8). Determining oxygen concentration at which CO concentration is the lowest might be helpful in the case when an automatic air stream regulation oxygen probe downstream the boiler is installed. For the studied furnace with periodic fuel supply, it can be assumed that an increase of CO concentration above the minimum value is caused also by an important decrease in temperature in the combustion chamber during the stand-by in pellet supply. Nitrogen oxide (NO and NO$_x$) concentrations depend mainly on the amount of nitrogen introduced into the furnace. As coniferous wood presents higher nitrogen content than deciduous wood, these concentrations were significant and varied from 239 (NO) and 369 (NO$_x$) mg/m^3 to 313 (NO) and 423 (NO$_x$) mg/m^3.

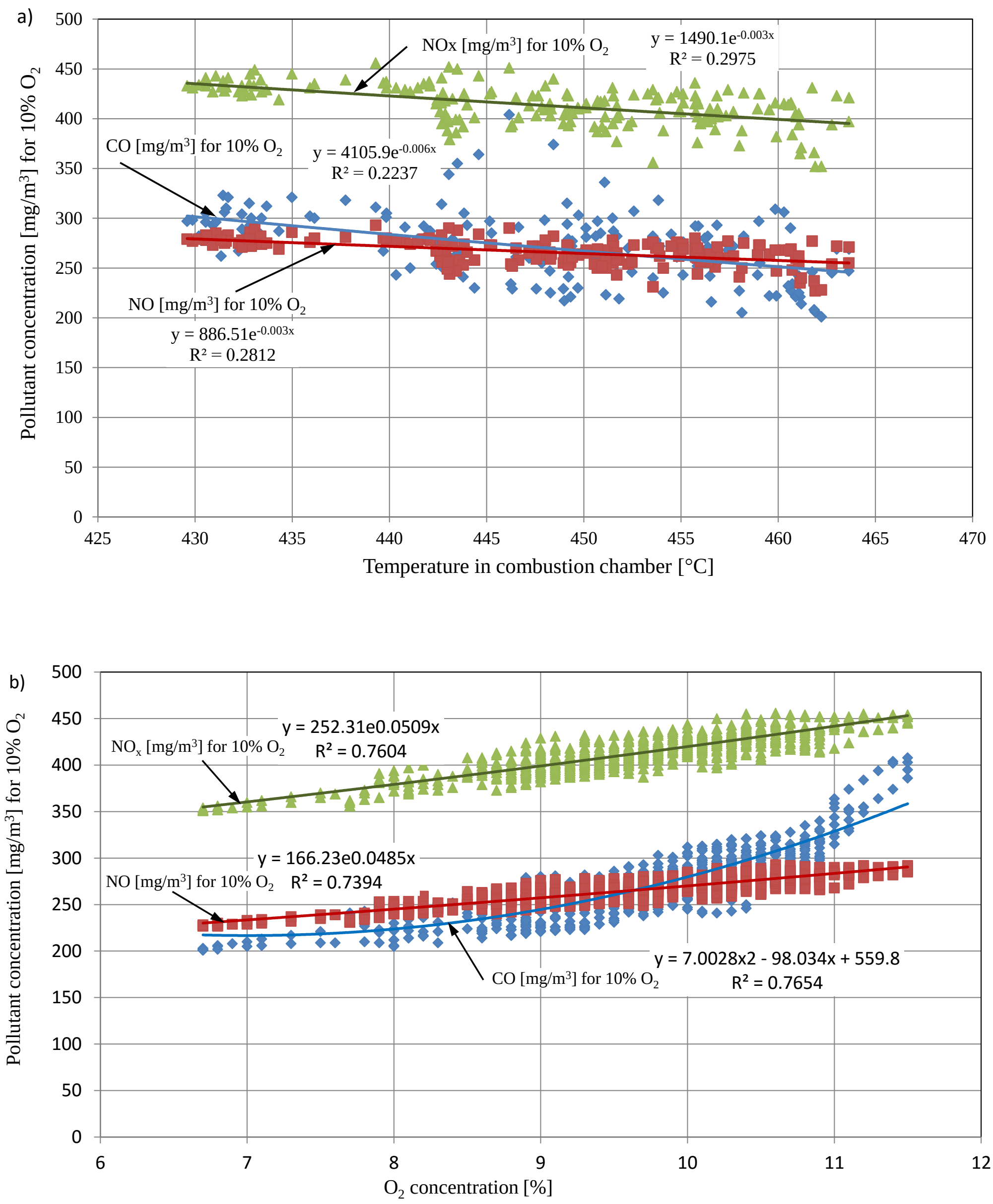

Fig. 6. Dependences of CO and NO, NO_x concentrations on temperature in the combustion chamber (a) and on oxygen concentration in the flue gas (b) for fuel mass stream 3.0 kg/h and periodic fuel supply: operation time 20 s, stand-by time 30 s

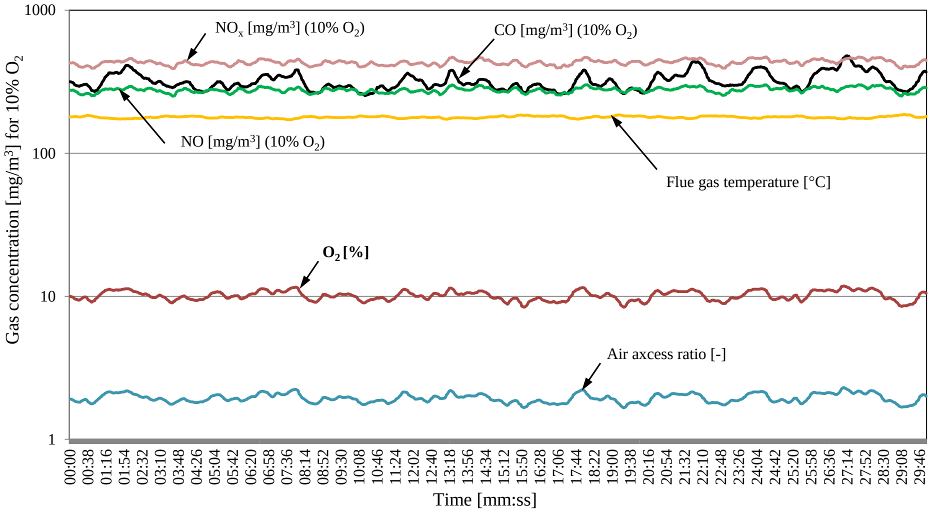

Fig. 7. Time dependences of pollutant concentrations and other parameters for 3 kg/h periodic fuel supply: operation time 60 s, stand-by time 90 s

A slight increase of NO and NO_x concentrations was observed when oxygen concentration increased and a subtle decrease when temperature in the combustion chamber increased. This means probably that in 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 course of 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. Dust concentrations of 30–50 mg/m^3 were much below the officially permitted values of 150 mg/m^3 [2].

4. CONCLUSIONS

Applying periodic fuel supply instead of continuous feeding mode does not necessarily have to come with a radical increase in CO concentration. Actually, the study has shown that in most conditions it was quite the opposite and CO concentrations were lower for periodic fuel supply. Generally, in order to keep CO concentration levels low one has to carefully select appropriate settings: fuel mass stream and air stream for both fuel feeding modes and additionally stand-by/operation time ratio for periodic fuel supply.

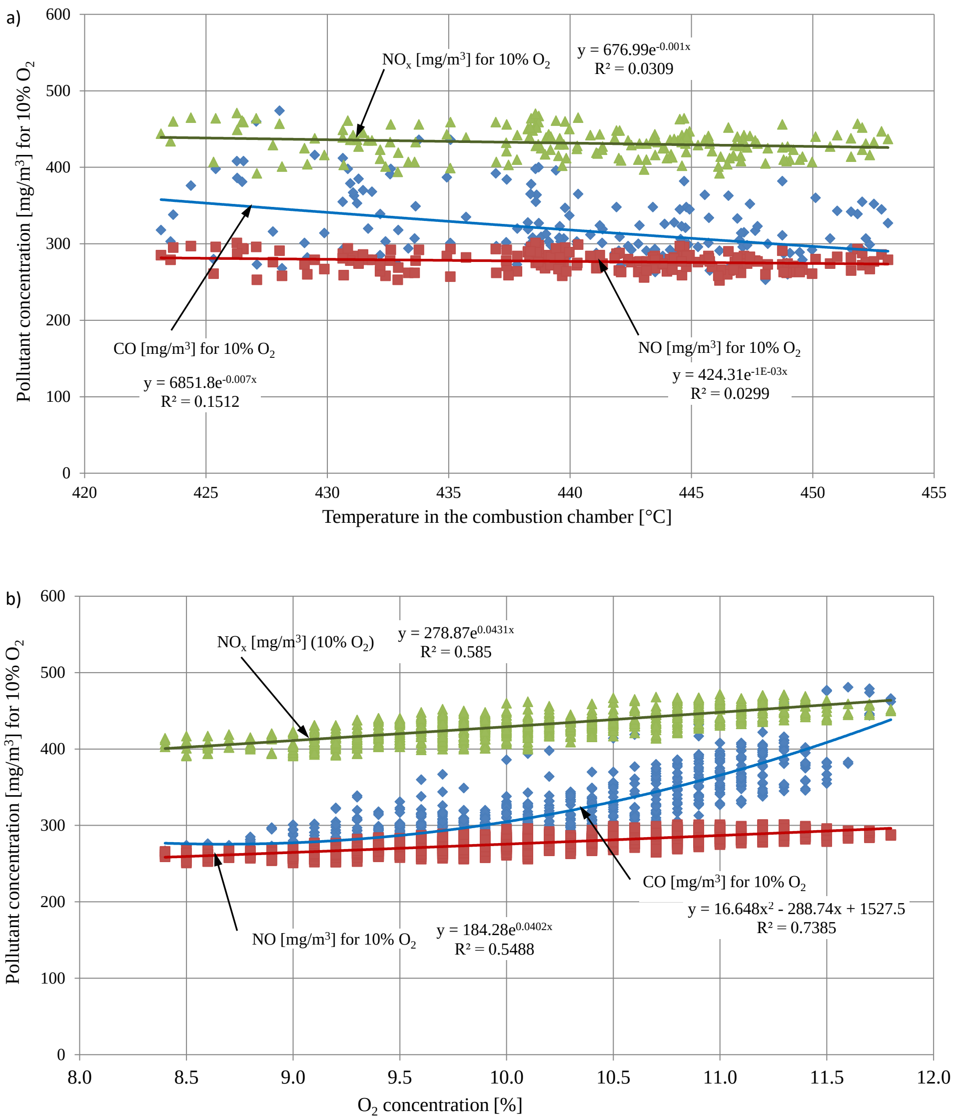

Fig. 8. Dependences of CO and NO, NO_x concentrations on temperature in the combustion chamber (a) and on oxygen concentration in the flue gas (b) for fuel mass stream 3.0 kg/h and periodic fuel supply: operation time 60 s, stand-by time 90 s

As boiler producers only indicate adequate settings for pure deciduous wood pellets, in the 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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