

# Experimental Study of Pollutant Concentrations from a Heat Station Supplied with Wood Pellets

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## Abstract

Carbon monoxide (CO), hydrocarbons (C<sub>x</sub>H<sub>y</sub>), nitric oxide (NO), nitrogen dioxide (NO<sub>2</sub>), and total particulate matter (PM) concentrations from wood pellet combustion were studied in two types of furnaces frequently used in Poland – over-fed (channel) and under-fed (retort) – integrated into two heating boilers with a nominal heat output of 15 and 20 kW located in a heat station. The over-fed furnace was situated additionally in the 20 kW boiler. Pollutant emission indicators were estimated. The conditions resembled the ones existing during wood pellet burning in domestic boilers, cheap and old construction, working without water heat storage or its capacity is insufficient. These boilers work without any proper automatic device equipped with an oxygen probe (lambda sensor) located downstream the boiler for air stream regulation. They also lack a proper automatic device for fluent fuel stream regulation in relation to the value of boiler water temperature. Therefore, when boiler water temperature reaches its maximum value (e.g. 85°C), the pellet screw feeder stops (fan is still operating) and reinitiates after a water temperature decrease of 5°C (unstable boiler operation). This is why temperature in the combustion chamber and oxygen concentration decreases significantly and carbon monoxide concentration increases rapidly and significantly. The impact of temperature in the combustion chamber on pollutant concentrations was presented. A significant difference in CO concentration values between stable and unstable operating conditions of three wood pellet combustion devices was observed and compared. The following results of CO concentrations were obtained: over-fed furnace in the 15 kW boiler – 609 mg/m<sup>3</sup> – stable operation, 19,000 mg/m<sup>3</sup> – unstable operation; over-fed furnace in the 20 kW boiler – 78 mg/m<sup>3</sup> – stable operation, 1,300 mg/m<sup>3</sup> – unstable operation; under-fed furnace in the 20 kW boiler – 336 mg/m<sup>3</sup> – stable operation, 2,000 mg/m<sup>3</sup> – unstable operation (concentrations normalized to 10% oxygen concentration in flue gas). A higher increase of CO concentration during decrease of temperature in combustion chamber in unstable boiler operation compared with stable operation was a consequence of significant oxygen concentration increase in combustion chamber when pellet screw feeder stopped, but fan was still operating. To avoid a radical increase of carbon monoxide concentration, it is necessary to gradually reduce fuel stream as water temperature in the boiler approaches its maximum value. Such a reduction should be performed by an adequate regulation of operations/break time of the pellet conveyer that does not cause high emissions of carbon monoxide.

**Keywords:** pollutant concentration, wood, boiler, heat station

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## Introduction

Small wood-supplied boilers present a significant emission of incomplete combustion products due to relatively low furnace temperature and unsatisfactory air distribution in the combustion region. It is estimated that in Germany the share of small-scale wood combustion systems contributing to the emission of incomplete combustion products (CO, C<sub>x</sub>H<sub>y</sub>, and soot) is between 16 and 40%, although their total energy production is only about 1% [1]. In Poland, the proportion of incomplete combustion product emission per energy unit is similar or even higher, as customers more frequently use cheap boilers of simple and old design with low heat efficiency, that lack a good automatic air supply device. Recently, in order to reduce the emission of incomplete combustion products, wood pellets have been introduced to the heating boilers instead of wood logs [2].

In Poland, many heat stations work with cheap and old wood boilers equipped with pellet burners. These boilers work without any proper automatic device equipped with an oxygen probe (lambda sensor) located downstream the boiler for air stream regulation. They also lack a proper automatic device for fluent fuel stream regulation in relation to a value of boiler water temperature. When boiler water temperature reaches its maximum value (e.g. 85°C), pellet screw conveyor stops and reinitiates after a water temperature decrease of 5°C. This is why temperature in the combustion chamber decreases significantly and carbon monoxide concentration increases rapidly and significantly. In such unstable conditions, carbon monoxide concentration is much higher than during stable operation of the boiler. In the heat stations mentioned above, boiler water temperature frequently reaches its maximum value when heat demand for central heating and hot water preparation is lower than the current boiler heat output and when there is no water heat storage or its capacity is insufficient.

Most studies describe emissions from boilers and burners working in stable conditions during deciduous burning [3-14]. In these cases, carbon monoxide concentration depends on boiler heat output, type of boiler and burner, and air excess ratio. These studies refer to boilers with a heat output between 10 and 30 kW, for which carbon monoxide concentration varies between 50 and 2,600 mg/m<sup>3</sup> (concentrations normalized to 10% oxygen in the flue gas). For comparison, while firing coniferous wood logs (which burn more intensively than deciduous wood logs because of high resin content), CO concentration values of about 6,500 mg/m<sup>3</sup> were obtained [15]. However, [16] was found to present emission results for boiler operation in unstable conditions. In this study, carbon monoxide concentration versus temperature in the combustion chamber during the pellet ignition process was analyzed. It was observed that when temperature in the combustion chamber increased from 200°C to 350°C, carbon monoxide concentration decreased from approximately 17,000 mg/m<sup>3</sup> to approximately 1,000 mg/m<sup>3</sup>. Oxygen concentration in the flue gas decreased from approximately 20% to approxi-

mately 12%. In [17, 18], carbon monoxide emissions of combined pellet and solar heating system were presented. A rapid increase of carbon monoxide concentration was observed when the pellet boiler was turned of.

The concentration of nitrogen oxides NO<sub>x</sub> in the flue gas during wood burning is not high, mainly below 400 or even 250 mg/m<sup>3</sup> (all concentrations mentioned above are normalized to 10% of oxygen concentration in flue gas), as nitrogen content in mainly wood is below 0.6 wt% and furnace temperature in most cases does not exceed 1,000°C. Sulfur content in wood is very low, therefore SO<sub>2</sub> concentration is negligible. PM concentration in the flue gas is usually low, compared to i.e. hard coal combustion due to the fact that ash content in wood is about 1 wt% and in hard coal mainly between 6 and 12 wt%. Sometimes waste wood used for pellet production contains much more ash originating mostly from contamination in the form of sand received during logging, handling, or storage of raw material. On the other hand, if the flue gas coming from the furnace immediately touches the cold surface of boiler heat exchanger, soot can appear, sometimes causing a significant increase in PM concentration in the flue gas. C<sub>x</sub>H<sub>y</sub> concentration can be low if the combustion process is complete or if the flue gas leaving the furnace immediately touches the cold surface of the heat exchanger. In this case C<sub>x</sub>H<sub>y</sub> can be transformed into soot [19, 20]. Sometimes ash slagging phenomenon can be observed in furnaces during pellet combustion [21-23] originating problems in furnace operation that result in low boiler heat efficiency and high CO concentration in the flue gas. Generally, wood ash slagging tendencies appear at temperatures exceeding 1,000°C [24], but sometimes they also occur at lower temperatures if fuel contains alkali substances.

## Experimental Procedures

Experiments were carried out in a full-scale heat station located in a laboratory belonging to Poznań University of Technology (Division of Heating, Air Conditioning and Air Protection, Institute of Environmental Engineering) in conditions resembling those existing in domestic boilers. The studied boilers and pellet furnaces are commonly used in Poland.

Pellets were fired in two types of furnaces: retort and channel (frequently used in small heating boilers). For experimental purposes the channel furnace was first installed in the 15 kW boiler and then in the 20 kW boiler substituting the pellet retort furnace. The retort furnace was installed only in the boiler with a nominal heat output of 20 kW. The boilers had no ceramic elements inside the combustion chamber.

The boilers cooperate with a 900 l water heat storage equipped with a special mixing and pumping device. This device enables water flow in the boiler only after reaching 64°C. In the wood combustion process, this is crucial for minimizing soot formation by keeping the combustion chamber walls hot.

Pellets are supplied from storage by means of a fixed-speed screw conveyer and then a horizontal fixed-speed screw pellet feeder of each furnace introduces pellets to the burning region. Each pellet furnace is equipped with its own electrically heated automatic ignition device. The fuel stream is regulated manually by modifying the time of screw feeder operation and stand-by in order to obtain good combustion conditions, low CO concentration in flue gas, and the desired heat output of the boiler. Air stream can be modified manually by fan speed regulation, ranging from 10 to 100% of its maximum value.

When boiler water temperature reaches its maximum value (e.g. 85°C), the pellet screw feeder stops and reinitiates after a water temperature decrease of 5°C (unstable boiler operation). The fan is operating the whole time, reducing air stream when the pellet feeder stops. Experiments were performed for stable and unstable boiler operation. Pollutant concentrations versus temperature in combustion chamber were observed. All the obtained data (measured continuously) were transmitted to a personal computer *via* a data acquisition system.

The experiments for boiler stable operation lasted continuously for 10 hours (test runs) for each combustion device (boiler with a pellet furnace). For each test run of boiler stable operation, parameter values were collected every 10 seconds and for unstable boiler operation every 2 seconds. Uncertainty intervals were calculated for all measurement results with a 0.95 probability.

Gas pollutant concentrations were measured in the flue gas downstream the boiler as well as flue gas temperature using a Vario Plus (MRU) flue gas analyzer (Germany). CO and C<sub>x</sub>H<sub>y</sub> concentrations were measured using the infrared procedure. O<sub>2</sub>, NO, and NO<sub>2</sub> concentrations were measured with electrochemical cells. A gas analyzer calculated NO<sub>x</sub> concentration as a total of NO (transformed to NO<sub>2</sub>) and NO<sub>2</sub> concentration. PM concentration in the chimney was measured four times for every combustion device using a gravimetric dust meter equipped with isokinetic aspiration. The fuel stream was measured several times using a weighing device. The temperature in the combustion chamber was measured with a radiation shielded thermocouple PtRhPt connected with a temperature meter for value comparison. Heat received by the boiler water and boiler heat output were measured with an ultrasonic heat meter.

The study examined wood pellets of 8 mm diameter and 15 to 40 mm length. The chemical composition analysis (performed in an accredited laboratory) gave the following results (in wt%): C – 51.50±0.25, H – 7.58±0.11, N – 0.35±0.05, O – 40. Ash content was measured in the laboratory of Poznań University of Technology and was always below 1 wt%. Lower heating value of 18 MJ/kg was provided by the pellet producer.

Pollutant emission indicators were only estimated as flue gas in the chimney and were not measured during the experiments. Flue gas and air volume obtained from 1 kg of fuel (wood pellets) under stoichiometric conditions was calculated using formulas presented in [25], depending on lower heating value and in real conditions also on air excess ratio.

Boiler heat efficiency was calculated once for each combustion device, as heat transferred to the boiler water divided by fuel mass multiplied by fuel lower heating value. During the entire study pellet mass stream in each furnace was almost identical, approximately 3.5 kg/h.

## Results

The results obtained during the measurements performed in the heat station are presented below. They include mean values and uncertainty intervals (Table 1) obtained during pellet combustion in the over-fed furnace placed in both boilers (15 and 20 kW) and the under-fed furnace situated in the boiler with a nominal heat output of 20 kW. These results were obtained during stable operation of the boilers. Carbon monoxide concentration versus temperature in the combustion chamber for stable and unstable operation of the boilers is presented in Figs. 1-3 (during unstable boiler operation, water temperature reaches its maximum value, and the pellet screw feeder stops and reinitiates after a water temperature decrease of 5°C. The fan is operating the whole time, reducing air stream when the pellet feeder stops). For unstable boiler operations, regression curves were situated and correlation coefficients were calculated.

Boiler heat efficiency was calculated for the 15 kW boiler with channel furnace, the 20 kW boiler with channel furnace, and the 20 kW boiler with retort furnace during stable operation with a result of 71%, 86%, 84%, respectively.

## Discussion of Results

The results obtained during stable operation of the boilers (Table 1) were comparable to results obtained during other investigations [3-14]. CO concentration was not high and did not exceed the permitted value of 3,000 mg/m<sup>3</sup> (concentrations normalized to 10% of oxygen concentration in flue gas) [26].

The experiments used an over-fed furnace, very similar to the one used in the studies presented in [4], as well as an under-fed furnace, identical to the one presented in these studies [4]. The pollutant concentration and emission indicator values presented for stable boiler operation (Table 1) resemble these obtained in studies [4].

While using the same over-fed furnace and an identical fuel stream in two different boilers, considerably varying results were obtained for carbon oxygen concentrations (Table 1).

The lowest CO concentration in the flue gas was observed during pellet combustion in the over-fed furnace installed in the 20 kW boiler. The highest CO concentration was seen for the same furnace placed in the 15 kW boiler (Table 1). This indicates that shape, size, and construction of the combustion chamber have a huge influence on CO concentration values. Boiler heat efficiency (Table 1) mostly depends on boiler type and furnace construction and only

Table 1. Mean parameter values and uncertainty intervals, pollutant emission indicators for pellet combustion in over-fed and under-fed furnaces-stable operation of the boilers.

	The 15 kW boiler with over-fed pellet furnace	The 20 kW boiler with over-fed pellet furnace	The 20 kW boiler with under-fed pellet furnace
O <sub>2</sub> concentration [%]	17.1±1.1	14.6±0.6	14.3±0.6
Air excess ratio $\lambda$	5.9±1.4	3.5±0.4	3.1±0.3
Temp. in combustion chamber [°C]	761±106	510±23	482±31
Flue gas temp. [°C]	206±23	128±11	148±16
Boiler heat output [kW]	7.7±2.2	10.0±0.7	11.7±3.8
CO concentration [mg/m <sup>3</sup> ] (10% O <sub>2</sub> )	609±290	78±35	336±56
NO concentration [mg/m <sup>3</sup> ] (10% O <sub>2</sub> )	23±9	57±10	121±9
NO <sub>x</sub> concentration [mg/m <sup>3</sup> ] (10% O <sub>2</sub> )	36±15	88±15	185±14
PM concentration [mg/m <sup>3</sup> ]	5.0±0,6	3.6± 0.4	1.6±0.7
CO emission indicator [g/MJ]	0.393±0.216	0.031±0.018	0.088±0.017
NO emission indicator [g/MJ]	0.016±0.003	0.022±0.01	0.032±0.002
NO <sub>x</sub> emission indicator [g/MJ]	0.019±0.004	0.034±0.007	0.048±0.004
PM emission indicator [g/MJ]	0.0029±0.0007	0.0014±0.0003	0.0004±0.0002

slightly on CO concentration value in the flue gas. PM concentration values were also much below the permitted value of 150 mg/m<sup>3</sup> [26]. PM deposits appeared on horizontal parts of the boiler heat exchanger surfaces in case of the 15 kW boiler. Sometimes pellet ash slagging tendencies were observed in the furnaces. During all experiments C<sub>x</sub>H<sub>y</sub> concentrations were negligible, although soot could be observed in the flue gas exhausted through the chimney. NO and NO<sub>x</sub> concentrations were low in the case of all combustion devices (Table 1), also during unstable operation of the boilers. They depended mainly on nitrogen content in wood pellets and also slightly on temperature in the combustion chamber (as it was below 1000°C and the difference between mean temperature values was not large [27]).

A considerable difference in carbon monoxide concentration values was noticed during the test runs for stable and unstable boiler operation (Figs. 1-3). Significant influence of temperature in the combustion chamber on CO concentration was noticed during unstable boiler operation, for all combustion devices (when boiler water temperature reached its maximum value and pellet screw feeder stops and reinitiates after a water temperature decrease of 5°C. The fan is operating the whole time, reducing air stream when pellet feeder stops (Figs. 1-3). As the temperature in the combustion chamber decreased (Figs. 1-3), CO concentration increased significantly in every case of boiler/ furnace devices. This could indicate that after pausing the pellet feeder, while the fan is still in operation but with considerably lower performance, an increase in carbon monoxide concentration is caused not only by temperature reduction but at the same time by significant oxygen concentration increase. As a comparison, as shown in [16], carbon

monoxide concentration from a pellet-supplied boiler with a nominal heat output of 13 kW was noticeably increasing after exceeding the oxygen concentration level of 13% in the furnace (NO<sub>x</sub> concentration increase was negligible). This would explain the meaning of Figs. 1-3, where one can clearly see a greater influence of temperature reduction on carbon monoxide concentration increase for boiler operation in unstable conditions, as compared to stable operation for all three devices (boiler/furnace).

Having analyzed Figs. 1-3, it can be stated that an increase in carbon monoxide concentration in combination with temperature decrease in the combustion chamber depends not only on the furnace type but also on the boiler this furnace operates in. The smallest oxygen monoxide

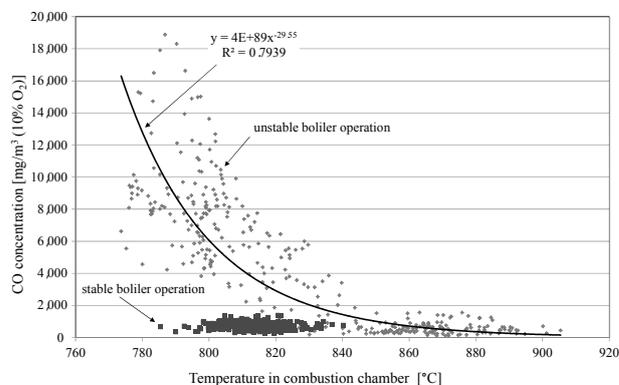


Fig. 1. CO concentration versus temperature in combustion chamber during a one-hour test run performed in the 15 kW boiler with over-fed pellet furnace – stable and unstable operation of the boiler, y – regression curve, R – correlation coefficient.

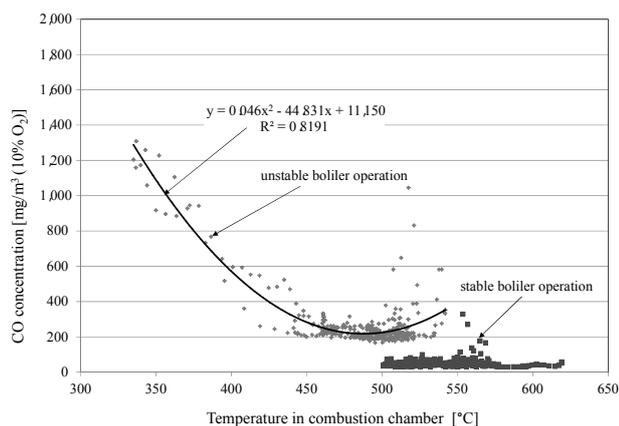


Fig. 2. CO concentration versus temperature in combustion chamber during a one-hour test run performed in the 20 kW boiler with over-fed pellet furnace – stable and unstable operation of the boiler,  $y$  – regression curve,  $R$  – correlation coefficient.

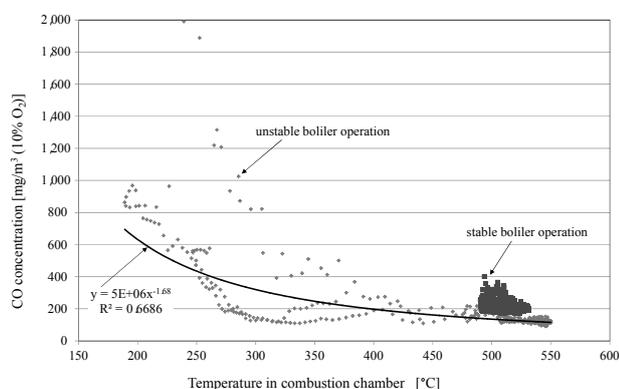


Fig. 3. CO concentration versus temperature in combustion chamber during a one-hour test run performed in the 20 kW boiler with under-fed pellet furnace – stable and unstable operation of the boiler,  $y$  – regression curve,  $R$  – correlation coefficient.

concentration increase in correlation with temperature reduction in the combustion chamber (for unstable conditions) was observed for the under-fed furnace working within the 20 kW boiler; the biggest, for the over-fed furnace placed inside the 15 kW boiler.

Unstable boiler operation occurs frequently in heat stations in practice, especially in combined heating systems, e.g. pellet and solar [18], and in other heating systems if water heat storage capacity is insufficient, boiler heat output (manually set) is excessive and heat demand for central heating and hot water preparation is too small.

## Conclusions

The study has shown that an increase in carbon monoxide concentration in relation to temperature reduction in the combustion chamber is greater in cases when the wood pellet feeder is stopped (unstable boiler operation) than in

cases of stable boiler operation. This is most probably a result of the fact that in the studied case, after the pellet feeder is stopped the fan still continues to provide air to the furnace, although in smaller amounts (to sustain the combustion process). The increase in carbon monoxide concentration is then caused by two factors: temperature reduction in the combustion chamber and a considerable oxygen concentration increase. To avoid a radical increase of carbon monoxide concentration, it is necessary to gradually reduce fuel stream as water temperature in the boiler approaches its maximum value. Such a reduction should be performed by an adequate regulation of operations/break time of the pellet feeder that does not cause high emissions of carbon monoxide.

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