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*Original Research*

# Main Causes of $NO_x$ Emissions by Low-Power Boilers

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### Abstract

This article presents a thorough analysis of the main reasons behind the generation of nitrogen oxides ($NO_x$) during combustion of coal-derived fuels in low- and medium-power boilers. Tests were made based on data from real-exiting heating systems operating in Poland over the last three years. Results of analytical research were used to conduct original experimental tests indicating the main problems of scattered municipal power engineering in Poland.

**Keywords:** nitrogen oxides, boilers, solid fuels, heating systems, emission of pollutants

## Introduction

Emissions of nitrogen oxides have serious consequences for the natural environment and, directly, human health. Significant quantities of $NO_x$ released to the atmosphere are the reason that acid rains have such a harmful impact on the global ecosystem. When inhaled, they irritate lungs, leading to pulmonary oedema, cause falls in blood pressure, and are harmful to the nervous system.

Today we recognize basic mechanisms of forming nitrogen oxides in the combustion process: thermal, prompt (also referred as flame), and fuel. Nitrogen oxides formed by those mechanisms are usually named, respectively thermal, prompt, and fuel. Thermal and prompt $NO_x$ are formed from air nitrogen, and fuel $NO_x$ is produced as a result of oxidation of nitrogen compounds in fuel, most often called 'fuel nitrogen' ($N_f$) [1].

Recognizing the main reasons for nitrogen compound formation enables us to undertake numerous actions to reduce their emission. The methods used most often for emissions reduction consist of reduction of the combustion temperature and in controlling the process of mixing fuel and air. Such methods of reducing temperature are described as primary methods and they comprise: application of low-emission burners, two-zone (non-stoichiometric) combustion, recirculation of combustion gases, and reduction of air-fuel equivalence ratio. These methods may be applied at the same time, which improves their efficiency (however, higher CO emissions may be a side effect of using them). Secondary methods of $NO_x$ emissions limitation include selective catalytic reduction (SCR) and selective non-catalytic reduction (SNCR), as well as integrated desulphurization and denitrification of flue gases [2].

For many years the issues of reducing nitrogen oxide emissions have been strongly related to the power industry, where stringent standards concerning $NO_x$ emissions are in force. Table 1 presents permissible quantities of $NO_x$ emissions in $mg/Nm^3$ for energy facilities that did not obtain permission before 7 January 2013 [3].

Unfortunately, when we analyze the latest criteria concerning pollutant emissions by low-power solid fuel boilers included in the Polish Standards PN-EN 303-5:2012 [4], we do not find any information concerning nitrogen oxide emission limits in Poland. As for today, the only national certification institution for low-power boilers, which in guidelines concerning emission limits determines require-

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Table 1. Permissible quantities of $NO_x$ emissions in mg/Nm³ for energy facilities which did not obtain the permission before 7th January, 2013 [3].

| Total nominal power delivered in fuel [MW] | Hard coal and brown coal and other solid fuels | Biomass and peat | Liquid fuels |
|---|---|---|---|
| 50-100 | 300<br>400 (pulverized brown coal) | 250 | 300 |
| 100-300 | 200 | 200 | 150 |
| > 300 | 150<br>200 (pulverized brown coal) | 150 | 100 |

Table 2. Emission limits for combustion according to criteria of IChPW for "the sign of ecological safety" [5].

| Criterion | Boiler class | Emission rates in mg/m³ for 10% $O_2$, with reference to dry flue gases | | | | | |
|---|---|---|---|---|---|---|---|
| | | CO [mg/m³] | $NO_2$ [mg/m³] | DUST [mg/m³] | TOC [mg/m³] | 16PAHs [mg/m³] | B(a)P [ug/m³] |
| Boilers with manual feed | B | ≤ 5000 | ≤ 400 | 200 | ≤ 150 | 15 | 150 |
| | A | ≤1200 | 400 | 125 | 75 | 5 | 75 |
| Boilers with continuous automatic feed | B | ≤ 3000 | ≤ 600 | 150 | ≤ 100 | 5 | 100 |
| | A | ≤1200 | 400 | 125 | 75 | 5 | 75 |

ments for $NO_x$ concentrations in dry flue gases for boilers with both manual and automatic feed, is the Institute for Chemical Processing of Coal (IChPW) in Zabrze. Table 2 presents a list of all requirements needed to obtain "the sign of ecological safety" [5]. The problem arising from a lack of legal regulations on $NO_x$ emissions from solid fuel low-power boilers became crucial when correlated with statistical data on pollutant emissions generated by the municipal and household sectors.

The latest data published by the Central Statistical Office of Poland (GUS) indicate that in Poland, 84% of homes in cities and 65% of homes in villages have central heating. Additionally, it should be stated that 70% of this number is small residential buildings. Annually, 11% of total consumption energy in Poland is used only for heating small residential buildings. In the case of such a decentralized energy system a solution influencing the reduction of pollutant emissions is the application of heating devices fuelled by natural gas. But the same statistical yearbook says that in Poland only 73% homes in cities and 20% homes in villages have access to gas networks. Therefore, boilers fed with solid fuels are the main source of thermal energy in Poland [6].

## Analysis of Low-Power Boiler Operation in Conditions of Real Heat Load

To draw the scale and reasons of high $NO_x$ emissions in the municipal and household sectors, the authors have analyzed measurement data of operations of more than 500 boilers with automatic feed installed in Poland recorded during the last four years. Collected data came from boilers of power (ranging from 15 to 50 kW) used for heating single-family detached homes (central heating and production of domestic hot water). We registered data enabling us to identify unequivocally the quality and character of the combustion process during the whole calendar year. The most important data are:

- Outlet water temperature
- Temperature of water returning to the boiler
- Hot domestic water temperature
- Temperature of flue gases
- Temperature of air outside the building
- Temperature of air inside the building
- Value of water temperature set in the controller
- Value of water temperature set for the storage tank

Data being archived were subject to further analysis to find those appliances whose operation was registered in a continuous way, without any breaks in recording caused by, among others: boiler shut-down, control system failure, Internet link breakdown, registered system failure, or using the boiler only for seasonal heating. As a result of this selection, three objects were designated as reference objects for the purpose of further analysis. For those objects we have collected data on additional parameters describing insulating power of the building, volumetric flow rate of heating medium in the heating system, and type of fuel used. These parameters enabled us to determine thermal powers within which the boilers operated the entire calendar year. It should be noticed that in summer boilers were used only to produce domestic hot water, and in winter they were used to heat homes and produce domestic hot water.

Due to the fact that all three boilers under consideration were installed in newly-built detached homes, they complied with the latest standards concerning thermal insulating capacity as defined in the Regulation of the Minister of Infrastructure of 10 December 2010 amending the regulation on the technical conditions that should be met by buildings and their locations [7]. It allows for making the assumption that the main factor influencing the demand for thermal energy in winter was fluctuation in outdoor temperature. In summer the boilers were used only to produce domestic hot water, which, with their significant over-sizing when compared with the momentary demand for thermal energy needed to produce domestic hot water, caused them to be in so-called sustain mode most of the time, i.e. they used fuel for sustaining the combustion process.

Fig. 1a presents an exemplary characteristic of outdoor temperature fluctuations for one of the reference objects within the whole calendar year. Temperatures were registered for the region of central Poland, in a town in the second climatic zone of Poland. To compare the impact of outdoor temperature changes on the demand for thermal energy to be used for heating, Fig. 1b presents a list of momentary thermal powers for a building of 220 m², heated by a boiler with automatic feed at rated power of 24 kW.

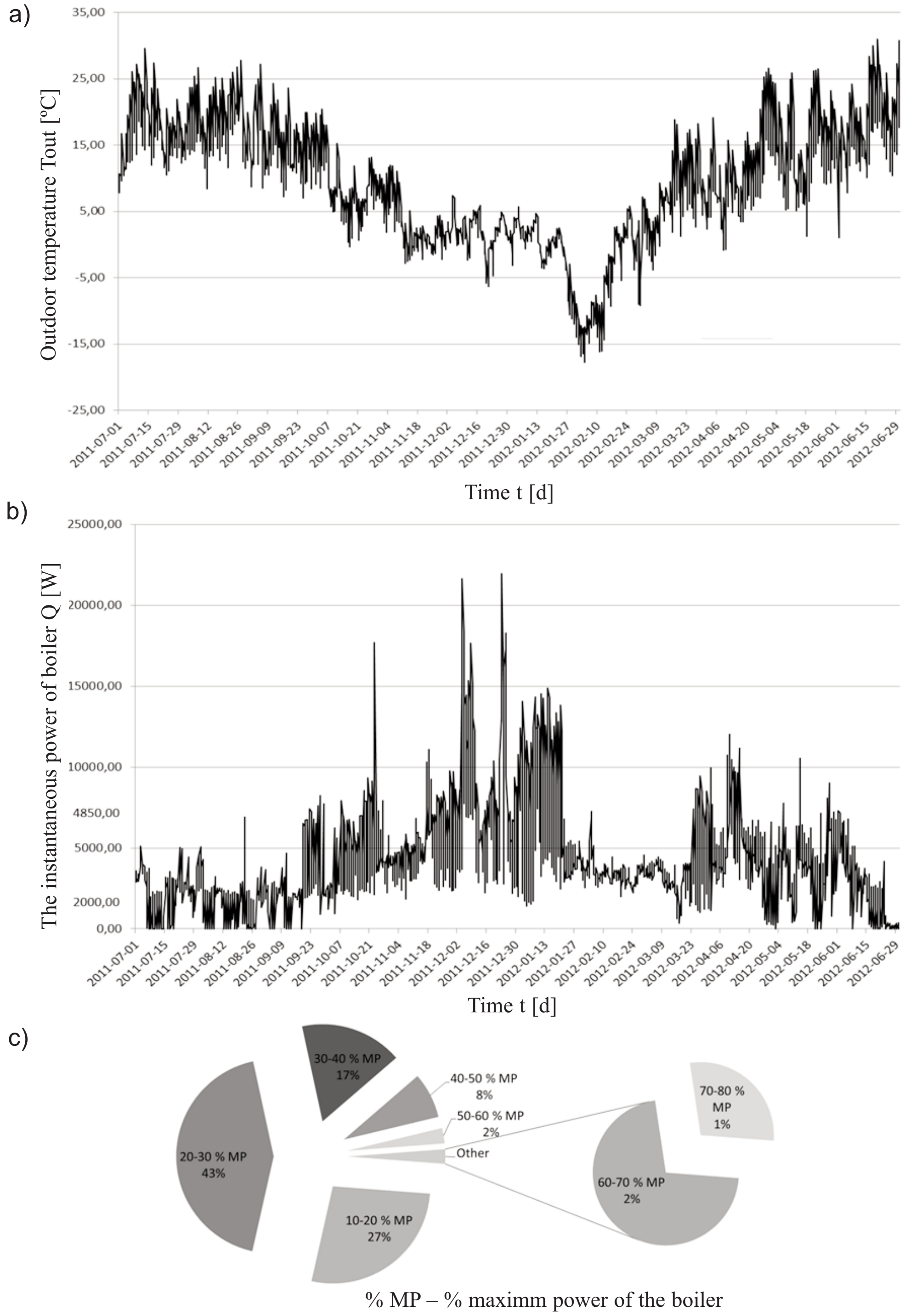


Fig. 1. Analysis of basic parameters within the calendar year; a) characteristic of outdoor temperature fluctuations within the whole calendar year, b) list of momentary thermal powers for the reference boiler within the whole calendar year, c) percentage breakdown of thermal powers within the calendar year.

The presented characteristics indicate that the boiler under consideration operated with the highest power only during a dozen or so days in December and January; however, the level of momentary thermal power did not exceed 15 kW, i.e. 62% of the boiler's rated power. During the rest periods of the heating season, the boiler's power ranged from 20 to 40% of the rated power.

In the heating off-season, due to a lack of the system's demand for thermal energy, most of the time boilers were in sustain mode. This is a situation when the temperature of the outlet water significantly increases above the set value and the fan stops operating. The temperature of flue gas decreases and reaches the temperature of water in the boiler. Due to a lack of oxygen, the level of carbon monoxide emission significantly increases as a result of an incomplete combustion process. The low level of the flue gas temperature causes condensation of water and acids being a factor of faster degradation of a boiler's steel parts. At the same time, fuel is still fed to the burner to sustain the combustion process. It is intended to prevent significant lowering of the furnace level in the automatic burner. This influences an additional increase of carbon monoxide emission. A lack of demand for thermal energy combined with the necessity to sustain the combustion process creates a situation when most thermal energy is used for boiler loss, which seems to be unprofitable.

Fig. 1c presents an overall percentage breakdown of momentary thermal powers of the reference boiler during the whole calendar year. Collected data show that no fewer than 43% of total operation time of the boiler under consideration operated with thermal power ranging from 20 to 30% of the rated power, while during 27% of operation time thermal powers did not exceed 20% of the rated power. The tested boiler operated with thermal power ranging from 60 to 100% of the rated power only during 3% of the whole calendar year.

Thorough analysis of boiler operation with respect to energy efficiency and emissions of substances such as carbon oxide and carbon dioxide was presented in prior publications. Results presented in those publications showed that the boiler's operation in summer is characterized by significant losses of thermal energy being a result of incomplete and non-total combustion. This may be proven by low levels of carbon dioxide and very high condensation of oxygen in exhaust gases. Operating in a low range of power is possible, but results in high inefficiency and a significant level of environmental effects of non-combusted solid and gas substances emissions.

Operating in winter with a thermal power achieving 54% of the rated power means better emission parameters, but when compared to the boiler's operation with the rated power, this process is still hazardous to the environment and highly inefficient.

In the case of solid fuels-fired boilers with automatic feed, the correct emission parameters are achieved only in the range close to the rated heating power [8].

The problem, which is clearly defined in prior publications, is incorrect selection of thermal power of the boiler compared to the real demand of the buildings. Presented data showed how powerful the influence of correct selection of the boiler's thermal power is on the quality and correctness of the solid fuels combustion process in boilers with automatic feed. Incorrect selection of the power results in highly inefficient operation of the boiler, which leads to its profitability drop and to the increase in the emission of pollutants related to the combustion process. For all cases under analysis the thermal power of boilers ranged from 10 to 50% of the rated power within the whole year. These values are demand values for which none of the currently produced heating appliances is able to maintain correct energy and emission parameters [9].

## Research Scope and Methodology

Due to the fact that nowadays there are no scientific studies on the of $NO_x$ emissions from low-power boilers fed with coal-derived fuels, the authors had to develop their own research methodology enabling determination of the main reasons for nitrogen oxide emissions from burning solid fuels in low-power boilers. This methodology was based on the assumption that researchers had data concerning ranges of thermal power within which boilers were operating in real conditions throughout the whole calendar year; however, they did not have data on the level of emissions of nitrogen oxides. This is why the authors decided to conduct tests on $NO_x$ emissions for the selected boiler's construction operating in laboratory conditions with the assumption that the power of the boiler would correspond to the power of a boiler operating in real conditions. Such research methodology would enable determining the ranges of thermal power for which the nitrogen oxide emissions from household and municipal heating reached the highest level. Data collected from real, existing objects allow us to determine the energy and operating parameters of boilers under consideration within the whole calendar year. However, since it was impossible to measure the nitrogen oxide emissions in real conditions for such a long period of time, we developed our own methodology of conducting research.

Archived data were analyzed thoroughly to determine representative ranges of thermal powers with which the chosen boilers operated. Due to a wide range of thermal powers, the following methodology of conducting laboratory tests was developed:

- For the selected design of the boiler with automatic feed of the construction and rated power close to the appliances operating in real conditions, the ranges of thermal powers for which tests would be conducted under laboratory conditions were determined.
- Emission testing will be carried out for the following rated powers: 100%, 54%, and 10% of the rated power. The value of 54% of the rated power corresponds to the demand of the boiler for thermal energy occurring only in winter. Operation using thermal power equal to 10% of the rated power is characteristic for summer, when boilers are used only to produce domestic hot water. Tests with the rated power will be carried out to deter-

mine the boiler's emission parameters when it operates with maximum power. Obtained results will act as reference values needed for further comparisons. Operation and maintenance documentation of the tested boiler indicated that it may operate with maximum thermal power of 17 kW.

- Due to a broken character of the boiler's operation in summer as a result of low demand for thermal power to produce hot domestic water, a series of tests aimed at determining the level of nitrogen oxides emission in summer will be conducted.

All tests were done in laboratories of the Chair of Thermal Engineering at Poznan University of Technology. To do them, an existing measuring stand, recently equipped with a modern archiving and analyzing station, was used. A diagram of the used test stand operating in the open system is presented in Fig. 2 [8, 10]. The test stand was equipped with a low-temperature water boiler with automatic fuel feed of the rated power of 17 kW. The boiler had a retort burner of the second generation (Fig. 2b). Every measurement was taken using the author's archiving and analyzing station built based on the automatic control device of the Adam 4000 series by Advantech. Fig. 2c presents the view of the measuring part of the test stand. Recording was done by a PC class computer using the measuring application created in the AdamView programming environment. A Testo 350 flue gas analyser enabled continuous measurement and recording of the results and was responsible for measuring emission levels of individual chemical compounds.

*Ekogroszek* hard coal of heating value 24.5 MJ/kg was used for all burning tests.

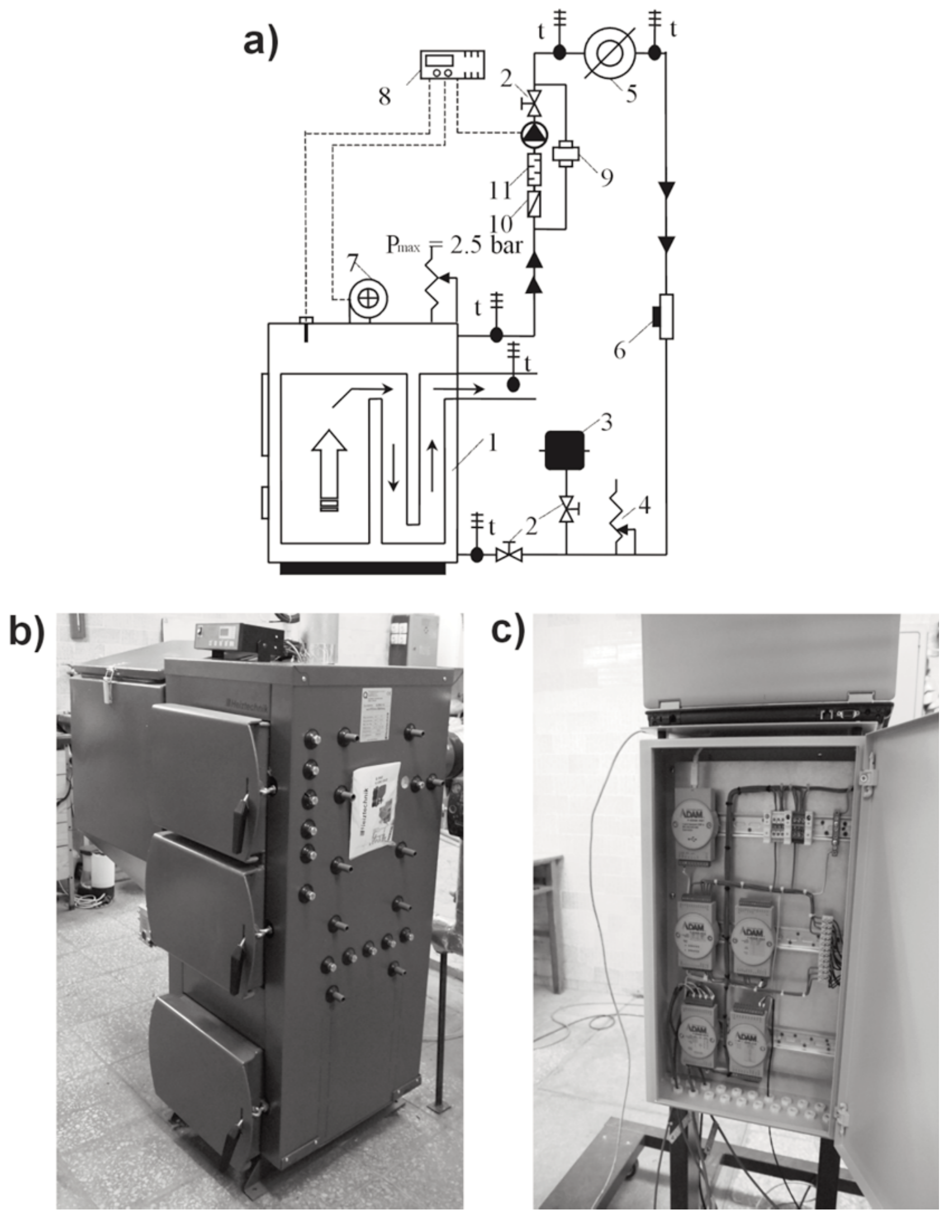


Fig. 2. View of test stand components; a) – Diagram of measuring stand: 1 – boiler, 2 – shut-off valves, 3 – open or close expansion vessels, 4 – safety valves for close central heating system set for 2.5 bar, 5 – heat exchanger assembly simulating the heat receiver , 6 – water meters for the water flowing through the system, 7 – blower, 8 – regulator controlling the boiler's operation, 9 – differential valve, 10 – check valves, 11 – strainer [10], b) – View of the selected boiler in the test stand [8], c) – Archiving and analyzing station.

## Analysis of the Obtained Test Results

Tests of burning solid fuels in a boiler with automatic feed for four main levels of thermal power corresponding to those of boilers operating in real conditions have been conducted In accordance with the developed research methodology. They were conducted for the following power ranges: 100%, 54%, and 10% and for the "broken" operation. Next, the analysis of the obtained data, particularly those concerning nitrogen oxide emissions produced by the model boiler operating in real thermal load, was conducted.

Due to the necessity of reflecting real parameters, the following assumptions as to the basic setpoints of the boiler's operation were made:

- For a boiler operating with maximum power, the value of temperature set on the boiler, determined according to guidelines of the PN-EN standard, was 75ºC. As a result of tests, the following values were achieved: water temperature $T_z$ was 75ºC, with temperature fluctuation of ±1ºC, and the average value of thermal power $\dot{Q}_k$ was 20.9 kW [8]. Those tests were conducted to determine the standard for comparison of $NO_x$ emissions for further results of tests.
- For analysis of the boiler's operation in conditions of maximum thermal load taking place in the period of the heating season, the following values of setpoint were assumed: water temperature on the boiler was set at 54ºC, and thermal load was set on the level of about 8 KW. As a result of tests, the following average values were achieved: water temperature $T_z$ was 53.4ºC, and average thermal power $\dot{Q}_k$ was 9.27 kW.
- For third phase, which should reflect the boiler's operation in conditions of minimum thermal load, the following assumptions were made: the setpoint of the outlet water was 48ºC, and thermal load was set at about 1.5 kW. During the boiler's operation the following values of parameters were achieved: average value of the outlet water temperature was about 49.8ºC and average thermal power calculated at the side of the heat exchanger, $\dot{Q}_k$, was 1.67 kW.

Fig. 3a presents the overall list of nitrogen oxide emissions recorded during operation of the select boiler within the three ranges of thermal power under consideration. This graph shows that no significant differences in nitrogen oxide emissions were noticed for the following ranges of power: 100, 54, and 10% of rated power. However, the lowest level of emission was noticed when the boiler operated with the rated power. During a two-hour period of recording, there were significant changes in the level of $NO_x$ emissions for each of the tested thermal powers. Knowing the mechanism of combustion process in low-power boilers, we may suppose that the noticed fluctuations of nitrogen oxide emissions resulted from the periodic character of the combustion process, dictated by temporal feeding fuel and by forming the shape of a furnace covered with ash and non-burned residues of parched fuel. To determine differences in emission levels as a function of current thermal power, average values for each of the ranges were calculated. For the tested powers the average value of nitrogen oxide emissions was as follows: 100% of thermal power for 360 mg/m$^3$, 54% of thermal power for 470 mg/m$^3$, and 10% of thermal power for 446 mg/m$^3$ (all calculations were made for dry flue gas with 10% condensation of $O_2$). Comparing the obtained results with limit values defined in the requirements for "the sign of ecological safety" determined by ICHPW, we have to state that for the rated power, the tested boiler fulfilled the requirements for class A (the highest one), and for the remaining ranges of thermal power it fulfilled requirements for class B.

Based on results of examining boilers' operations in real conditions in Poland, we stated that due to a lack of high demand for thermal energy during the whole calendar year, most of the year the boiler's operation has a periodical character. This means that since it is impossible to modulate the generated thermal power over a wide range, the boiler often goes into the sustain mode. It is a state when all set energy parameters of the boiler were achieved and the boiler operates only to sustain the combustion process. A demonstrative characteristic of the boiler's operation within one day for an average demand for thermal energy is presented in Fig. 3b. It could be seen that there are some breaks in the boiler's operation caused by achieving the programmed temperature of the outlet water and of the hot domestic water. Tests showed that such combustion was highly inefficient since the boiler had to produce incessantly thermal energy of about 1.5 kW to sustain the combustion process. In the scale of the whole year it is an important source of fuel consumption and emission of hazardous substances as carbon monoxide or dust to the atmosphere. To examine the impact of such a combustion process on the emission of nitrogen oxides, additional tests were conducted aimed at simulating the phenomenon described above. Fig. 3c presents the results of carbon monoxide and nitrogen oxide emissions for the phase of boiler going into the sustain mode and for the phase of increased demand for thermal energy.

Point I reflects the situation when the boiler goes to the sustain mode; the blowing fan is switched off, which results in reduction of nitrogen oxide emissions and a rapid increase of carbon monoxide emissions. This is due to cutting off the air access to the combustion process.

In point II, the boiler is in the sustain mode; due to a significant reduction of the combustion process intensity, the emission of nitrogen oxides remains at a steady level of about 150 mg/m$^3$, whereas the emission of carbon monoxide increases significantly up to the level of even 50,000 mg/m$^3$. This value exceeds a dozen times the current emission standards in Poland.

In point III, the situation of another increase of demand for thermal energy is simulated. At the moment of switching on the fan delivering air to the furnace chamber we can notice a marked fall in carbon monoxide emissions. This means the process of total and complete combustion. However, at the same time the condensation of $NO_x$ increases to a level exceeding 600 mg/m$^3$. This value significantly exceeds the standards in force, probably because the temperature increases rapidly in the combustion process, which may become a source of emissions of nitrogen oxides having roots in temperature processes.

## Conclusions

Authors of this article developed their own experimental method of estimating the impact of single family house heating systems on the high level of $NO_x$, based on the latest statistical data on emission of nitrogen oxides in Poland, pointing to the fact that the municipal and household sector is the fourth-largest source of emissions.

Within the framework of research a representative group of 500 automatic heating appliances fed with hard coal was selected. Their operation in conditions of real thermal load has been recorded for three years. Based on data from real objects we developed the methodology for laboratory tests that enables us to determine the emission levels of nitrogen oxides formed during the operation of small boilers fed with solid fuels used for heating single-family

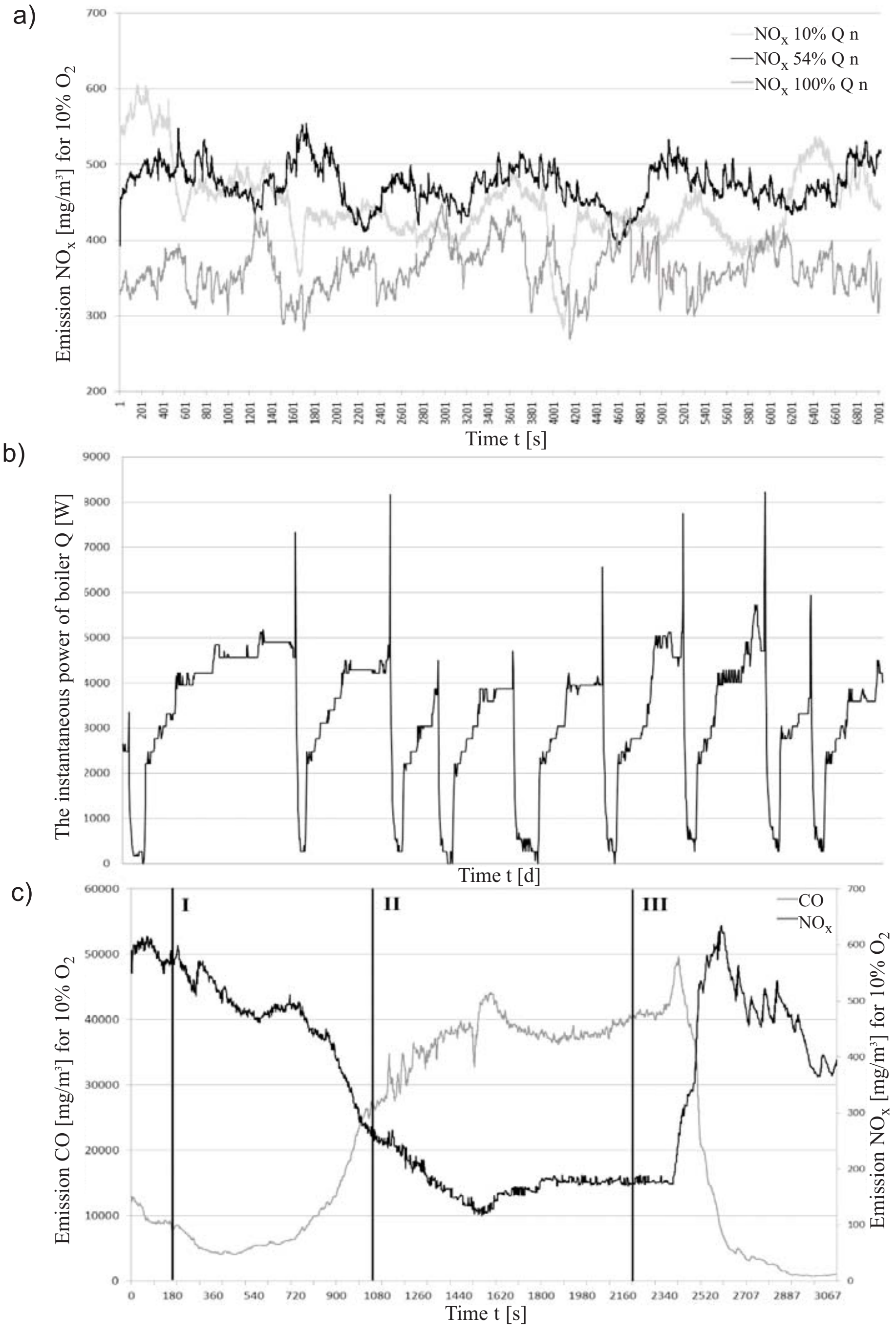


Fig. 3. List of emission and energy parameters of the tested boiler; a) overall list of nitrogen oxides emission for all three tests, b) characteristic of the boiler's operation within one day, c) emission of carbon monoxide and nitrogen oxides for discontinuous boiler's operation.

houses. Test results showed explicitly that low-power boilers operating within the whole range of thermal power did not cause excessive increases in emissions of nitrogen oxides from the process of combustion coal-derived fuel. This is influenced by a few factors, particularly by the fact that in the well-known mechanisms of producing $NO_x$ in the process of combustion coal-derived fuels in small boilers fed with solid fuels, most nitrogen oxides were formed from nitrogen compounds in fuels. This emission is directly connected with the chemical composition of the fuel and therefore it is difficult to eliminate it using primary methods for abatement of $NO_x$ emissions. However, literature research shows that for small boilers fed with wood pellet tests aimed at abatement of nitrogen oxide emissions are still conducted. It is done by proper arrangement of nozzles delivering overfire air to the furnace chamber (such air is necessary in the case of biofuel combustion due to the necessity of after-burning large quantities of volatile substances characteristic of bio-fuels). Authors of a demonstrative publication had modified the location of nozzles for overfire air, raising them from a height of 9 cm to 21 cm. As a result, they reduced the level of $NO_x$ emissions by more than 10%; however, this was linked with the increase of carbon monoxide concentration [11].

Analysing the tests results, authors of this article have noticed an important problem related to the significant increase of nitrogen oxide condensation during periodic operation of the boiler under tests. When it operates in the sustain mode, standards of carbon monoxide emission are exceeded a dozen times. When the boiler is achieving the set values of thermal power once again, the emission of nitrogen oxides increases significantly. Knowing basic mechanisms of forming $NO_x$ from combusting solid fuels it was stated that during a boiler's periodic operation the concentration of nitrogen oxides increased significantly due to two reasons. In boilers with automatic feed the combustion process proceeds in a methodical manner (a very small portion of fuel is burned at the same time); however, at the moment of transition from the sustain mode into the operation mode, there is a need for rapid increase of the boiler's thermal power, which depends on delivering a considerable quantity of fuel at one time, and in turn results in the increase of condensation of nitrogen oxides from fuel. At the same time, the temperature of the furnace grows significantly, which causes an increase in the quantity of nitrogen oxides forming in high-temperature processes. Unfortunately, in Poland such a situation occurs very often due the necessity of heating buildings in the spring and autumn seasons and due to a significant over-sizing of thermal powers of currently installed boilers fed with solid fuels.

A solution that would significantly contribute to abatement of emissions of both nitrogen and carbon oxides is to stop using boilers fed with solid fuels for production of domestic hot water in summer, and to select properly thermal powers of the installed boilers by taking into account the real demand for this power resulting from building energy calculations.

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