Archives of Environmental Protection
Vol. 47 no. 3 pp. 108–119

PL ISSN 2083-4772
DOI 10.24425/aep.2021.138469

Operational determinants of gaseous air pollutants emissions from coal-fired district heating sources

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Keywords: district heating, gaseous air pollutant emission, emission indicators, unstable conditions, heat only boilers.

Abstract: This study describes the correlation between emission of gaseous pollutants to the atmosphere and the combustion parameters of a coal-fired 25 MW heating capacity water boiler with mechanical grate (boiler type WR-25) in unstable working conditions: start-up, shutdown and loads below the technical minimum. Whereas measurements were made for a specific type and size of coal-fired water boiler with mechanical grate, the measurements and calculations are applicable to WR boilers with a different heating power as well as OR type steam boilers, which have a practically identical design. In sum, there are more than 1,000 coal-fired water and steam boilers of these types in Poland. In addition, the analysis reported in this paper highlights the important role played by boilers operating in unstable conditions in terms of emission of gaseous pollutants to the atmosphere. The conclusions are relevant for other boilers fired with gas, oil or biomass operating under conditions such as start-up, shutdown and loads below the technical minimum. This article fills a gap in air protection engineering practice and the literature with regard to indicators and emission standards, drawing on measurements of pollutant concentrations in the exhaust gases from unstable WR boiler working conditions. The measurements can be used to assess the emission of pollutants to the atmosphere in such boiler working conditions and their impact on air quality. The analyses presented were based on the authors' own measurements in WR-25 boiler technical installations using portable gas analyser GASMET DX-4000, which uses the FT-IR measurement method for compounds such as SO_2, NO_x, HCl, HF, NH_3, CH_4, and CO. Concentrations of CO, NO_x and SO_2 in exhaust gases were determined with multiple regression with the STATISTICA statistical software and with linear regression complemented by the "smart" package in the MATLAB environment. The study provides computational models to identify pollutant concentrations in the exhaust gases in any working conditions of WR-25 boilers.

Introduction

Reducing levels of pollutants in atmospheric air is a key concern in environmental protection. High amounts of emitted pollutants are an undesirable side effect of society's increasing demand for power, with major concerns linked to the combustion processes of fossil fuels at power stations (Beom et al. 2018). The highest emissions of atmospheric air pollutants (mainly: dusts, CO_2, SO_2 and NO_X) per unit of produced energy are achieved during the combustion of hard and brown coal (Różycka-Wrońska et al. 2014).

About 40% of Poland's population is served by District Heating (DH) systems; the 460 state and privately owned DH companies in the country maintain about 20,000 km of pipelines. All energy tariffs (heat and electricity) and development policies are government regulated. Annually around 162 TWh or 62% of the heat supply comes from CHP plants. Poland has a highly diverse network profile, with a range of sizes, sources and operating principles across the country. Currently, coal and gas are the main sources of heat generation. Warsaw boasts the largest DH network in central Europe, its 11 TWh meeting 80% of the city's annual heat demand delivered through 1600 km of pipelines. The sources include CHP plants and large-scale Heat Only Boiler (HOB) plants (Mazhar al. 2018, Holnicki et al. 2017).

The volume of pollution generated by a boiler mainly depends on the amount and characteristics of the fuel burnt, and the type of furnace, which determines the temperature of combustion and the concentration of oxygen in the first part of the flame (Montanari 2003, Ma 2010, Liu et al. 2017). Fuel quality directly influences boiler operation, efficiency, combustion processes and volume of emissions. In addition, the emissions index changes when the load of the heating plant (CHP or HOB) varies, which usually happens due to the weather and season of the year. In summer, outside of the heating season, the heating plant mainly works with one boiler, which produces consumable hot water and operates at ca. 20–30% of its nominal power. In the heating season, depending on outdoor temperature, the heating plant provides heat for space heating purposes and for consumable hot water demand, and reaches nominal power usually at temperatures below minus 20°C.

Optimal load and maximum energy efficiency occurs at 80–95% of a boiler's nominal power. At that point the WR boiler reaches its peak energy efficiency of 82% (boiler no. 2 in heating plant A – 78%). In these conditions heat is generated efficiently with minimum fuel consumption, stable furnace operating parameters and good dust removal. Work at optimal load, with almost perfect and complete combustion, delivers the lowest fuel consumption index and the lowest air pollution emissions index per unit of heat generated. At optimal load, monitoring can be restricted to the emission of gases: SO_2, NO_x and CO_2 alone. There are only trace amounts of VOC, HF, HCl, NH_3 and CO, as they are mostly caused by incomplete and imperfect combustion. There is a clear increase in emissions of these substances when combustion takes place in sub-stoichiometric conditions, such as start-up, shutdown and load below the technical minimum.

A number of legal regulations determine emission standards relating to fuel combustion. The Environmental Protection Law; Regulation of the Climate Minister; CAFE Directive; IED Directive; MCP Directive all determine emission standards for normal conditions of boiler operation. No documents set standards for unstable conditions, such as start-up, shutdown or loads below the technical minimum of boiler operation.

Observations of and experience with the operation of boilers in unstable conditions indicate that they lead to increased emissions of pollutants to the atmosphere. Therefore, it was assumed at the start of this study that a boiler operating under unstable conditions experiences significant changes in the concentration of pollutants in the exhaust gases. The novelty of this paper lies in developing an optimization model using multiple and linear regression that is valid for every make of WR boiler operating in unstable conditions.

Review of literature

China is currently the largest coal consumer in the world and coal has traditionally been its primary energy source. Although the share of coal in the energy consumption of China has decreased in recent years, it still accounted for 62% of its total energy consumption in 2016 and the total consumption of coal has increased by 14% in the last 10 years (Wang et al. 2019).

Searching for effective low carbon solutions for coal-fired DH sources is therefore just as important to China as it is to the world. The heating sector, mostly in the form of DH, is a large coal consumer (Lin and Lin 2017), burning 241 million tons in 2015. Heating generation will continue to depend on coal for decades to come, as the share of renewable energy in China is forecast to reach only 30% by 2050. Recently, the Chinese government introduced clean coal technologies into DH, as pilot projects aimed at energy saving and carbon reduction (Wang et al. 2019).

The geological resources of coal on the Earth, recalculated as primary energy units, are an estimated 18,000 EJ – two and a half times greater than oil reserves (Wilczyński 2013). The International Energy Agency (IEA) stated that the demand for coal in 2035 in OECD countries would be falling by 1.1% annually, while in China it would be going up by 2.1% each year (Wilk and Bocheńska 2003). Increasing demand for electricity and heat directly contribute to the eventual exhaustion of coal deposits in the world. With the present energy policy of the Chinese state, these deposits will suffice for over 180 years (Miller and Tillman 2008). Moreover, the Indian power sector is playing a key role in global emissions and efforts to mitigate climate change. Lifetime emissions over the next five decades from Indian coal-fired power generation could range from 18 to 39 Pg (Yang and Urpelainen 2019).

Global consumption of total energy in 2018 stood at 4,488.2 PJ. This figure differs slightly from the European average – gross inland energy consumption per capita in Poland in 2017 was 115.9 GJ, against the EU average of 137.1 GJ. An increase in global consumption compared to the previous year was observed in the case of hard coal, crude oil, natural gas, renewable energy and other sources, while there was a decrease in brown coal. Charcoal plays a significant role in energy sectors, especially in many developing countries (Marousek et al. 2014).

In Poland, the share of the various sources were as follows: hard coal 37.0%, brown coal 9.1%, crude oil 26.3%, natural gas 16.1%, renewables 9.3%, others 2.2%. Domestically sourced primary energy was mostly coal: hard coal with a 56.2% share in 2019, followed by brown coal with 15.2%. The share of natural gas in indigenous production was 5.5%, crude oil 1.5%, and the others, mostly renewables, 18.3% (Statistics Poland, 2019).

In 2018, the EU's consumption of hard coal and brown coal combined reached 596 million Mg, with about 60% of hard coal and more than 90% of brown coal used for electricity and heat production. Between 1990 and 2018 the number of member states of the EU producing hard coal fell from 15 to only 5: Poland, Czech Republic, Germany, United Kingdom and Spain. In 2018, Poland mined 63.4 million Mg of hard coal, 86% of the total EU production (Eurostat, 2019).

In Poland, coal is still a strategic source of energy and the vast majority of power plants burn mainly this fuel (EuroHeat and Power 2019, Demirbas 2006, Beom et al. 2018, Wasilewski et al. 2020). This is mostly due to its easy availability and price, as well as the fact that the plants were built in the 1970s and 1980s and designed for coal. Coal consumption in Poland initially rose steeply in the post-war period: it went from 51 million Mg in 1950 to a peak of 164 million Mg in 1980 before trending downward to 63 million Mg in 2018.

The significant reduction in coal consumption in Poland is due to the EU's energy policy, which incentivizes a switch from coal and toward renewable energy sources and, during the transition period, gas and oil combustion. The widely desired decarbonization of the EU economy (in Poland too) is revealing anomalies in its implementation that are throwing an increasingly critical light on the EU's climate policies and rigorous approach to the combustion of resources such as hard coal and brown coal. The EU itself is an important coal importer. Despite numerous decarbonization programs and a fall in coal mining in EU countries, the EU is actually experiencing rising demand for coal – both hard coal and brown coal. The biggest producer of brown coal in the world is Germany, where extraction of this resource is running at over 170 million Mg annually, providing over 30% of the national energy balance. Similar situations can be observed in the economies of some other countries.

WR water boilers with movable grate, powered with hard coal culm (coal particles type MI 20–0 mm or MII 10–0 mm) are installed in HOB plants, CHP plants and in industrial plants as heat generating units. A boiler is built in a two-pass system, with one pass in a gas-tight water-wall furnace chamber. Refractory lining is applied to protect front ceiling and sides walls of the furnace in the area of coal combustion.

The second pass is a finned convective bundle. The boiler is equipped with installations that control the combustion process, i.e., a secondary air installation over the grate and recirculation of exhaust gases under the grate. The mechanical grille is equipped with a cascade system of fuel supply, offering an option of simultaneous waste co-incineration (Różycka--Wrońska et al. 2014).

Refractory lining is applied to protect front ceiling and sides walls of the furnace in the area of coal combustion.

Materials and Methods

Outdoor air temperature is a major determinant of the changing heating load of a heating plant (HOB or CHP). In practical terms, summer is defined as a 24-hour average temperature above 10°C (three consecutive 24-hour periods), whereas the heating season is below 10°C. While average summertime demand for consumable hot water remains constant, the demand for space heating in the heating season is very changeable and highly correlated with outdoor temperatures. Therefore, to cover heat demand, the boiler requires a wide operational range. For this reason and in order to optimize the combustion process, heating plants are usually equipped with a few boilers. Selection of their sizes and number is based on an analysis of the distribution of consumer heat demand, the optimum combustion process, and minimization of operating costs. This analysis is illustrated with a heating power chart of heat generation and heat consumption for a DH system, which features heating power on the y-axis and outdoor temperature on the x-axis time.

Fig. 1 is a sample chart of heat generation/consumer heat demand, operating boilers and time of operation in relation to outdoor air temperature. Analysis of this graph clearly shows major differences between minimum heat demand for consumable hot water purposes in summer and maximum power in periods with the lowest temperatures, which then covers heat demand for consumable hot water and central heating (Popiołkiewicz 2006). Analysing it with reference to time and temperature, the summer period (above 10°C) lasts ca. 4000–5000 h (depending on the region) while the heating season lasts 3760–4760 h. The most visible increase in power and number of boilers operating can be observed at the start of the heating season. It begins after the average 72 h temperature drops below 10°C (usually early October) and, depending on the heat demand by customers, extra boilers start working. Analysis of the chart shows that in the heating season there are great fluctuations in heating plant load, depending mostly on outdoor temperature. The chart averages heat demand and, due to frequent temperature changes, boilers are often started up and shut down or work at a load below the technical minimum. At those times they generate larger unit emissions of typical pollutants, caused mainly by incomplete combustion.

To highlight typical fluctuations of boiler operation, Fig. 2 presents an illustration for the period of one (selected) year using the example of the real heating load of Heating Plant A. The polynomial trend line was used to process and evaluate the changes. A graphic interpretation of the trend for the analyzed data shows a rising line, which represents an increase in the assumed heating power of the heating plant for decreasing outdoor temperature and a falling line for increasing temperature. The trend line may be used to forecast heating power of the heating plant for future years. To present heat load trends for Heating Plant A, a fourth-degree polynomial

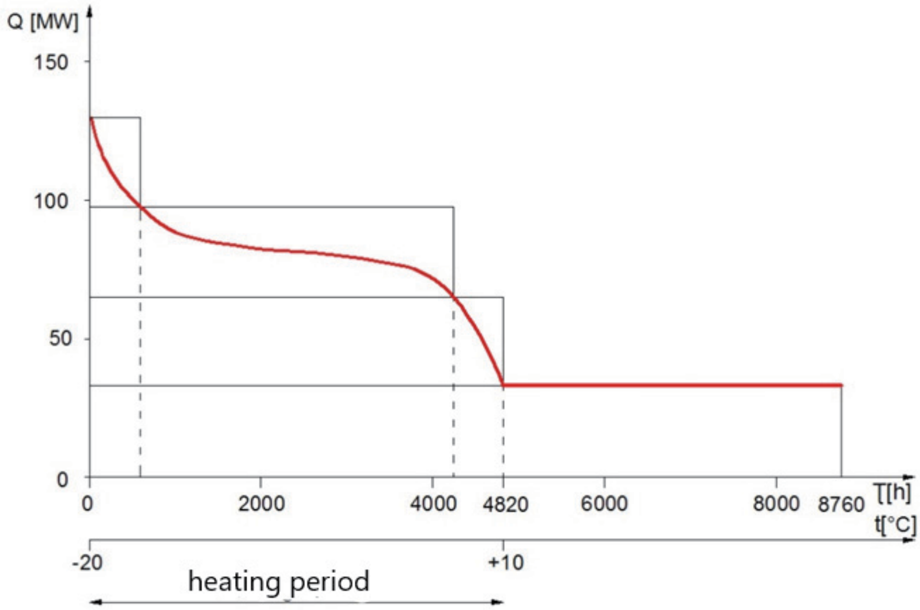

Fig. 1. Sample heating power chart of heat generation/heat consumption for a DH system in central Poland

was adjusted with the least squares methods, obtaining a high value of determination coefficient at the level of $R^2 = 0.8713$ (R^2 values are in the range of <0;1>).

The trend line provides a greatly smoothed graph of the dependence of boiler heating power on outdoor temperature. The great generalization is visible at the point of maximum load, where on the graph there is no clear increase in values. Neglecting this high heating power of boilers is, from the perspective of evaluating maximum emissions, unfortunate and even more so since the data used for the graph are data averaged for 24-hour periods, and so actual instantaneous powers were also higher than the presented ones. Finally, the trend line resulted in the graph being flat, eliminating values of the function that are the most important with regard to air protection. The real value turned out to be much higher (by ca. 50%) than the one that could be read from the trend line. This value was, however, only momentary due to a sudden and short temperature fall to minus 24°C. Due to such dynamic changes, this does not influence the averaged trend line (Wojdyga 2007). However, a sudden change in load has a negative impact on the maximum emission of pollutants to the atmosphere.

Fluctuations in boiler loads occurring over the year have a significant impact on selection of the most beneficial temperature of exhaust gases. The greatest impact on selection of the temperature of exhaust gases is exerted by the structure of the heating surfaces of the boiler and the design of the chimney connected to the boiler. Exhaust gas temperature may not fall lower than the dew point. Boiler energy efficiency changes as its productivity falls – usually with a small fall, at first it rises a little, and then, with further falls it decreases. Then decreasing boiler productivity causes a temporary fall to nominal values – energy efficiency is going up and then there is a further change in productivity where energy efficiency decreases again. At the same time, the temperature of exhaust gases also goes down and emissions of pollutants go up, especially when boiler capacity falls below 30% of the nominal heating power (Pronobis 2002).

Load fluctuations of heating plants also occur when starting up and shutting down boilers. Starting up a cold boiler is done very slowly – water temperature in the boiler should increase gradually (1°C /min) in a process taking 3 to 3.5 h. During this time the installation does not work at full load – there is low efficiency, lower dust removal efficiency, increased fuel consumption and unstable parameters of furnace operation. These conditions greatly increase the emission of pollutants to the atmosphere (from incomplete and imperfect combustion) and this continues until the temperature in the furnace chamber and combustion conditions stabilize and the nominal heating power of the boiler is reached. Therefore, it is very important to conduct the boiler start-up process very slowly and as instructed by the manufacturer.

Boiler start-up is performed as follows:

- start the circulation pump;
- ventilate the boiler and start the exhaust fan;
- light up the firelighter on the grate;
- start the air blowing fan;
- after lighting coal on the grate – the grate starts moving at an appropriate speed depending on the boiler heating load (the combustion process is controlled by the air flow rate, thickness of fuel layer and speed of the grate belt);
- turn the air heater on after reaching exhaust temperature of 150–170°C.

When the boiler is being shut down, the installation evidently does not operate at full load. This has similar effects to boiler start-up: lower efficiency, lower dust removal efficiency, increased fuel consumption and unstable furnace work parameters. The work of a boiler unit at changeable load or during shutdown results in greater emissions of gaseous pollutants into the atmosphere. Boiler shutdown is performed as follows:

- stop the fuel supply;

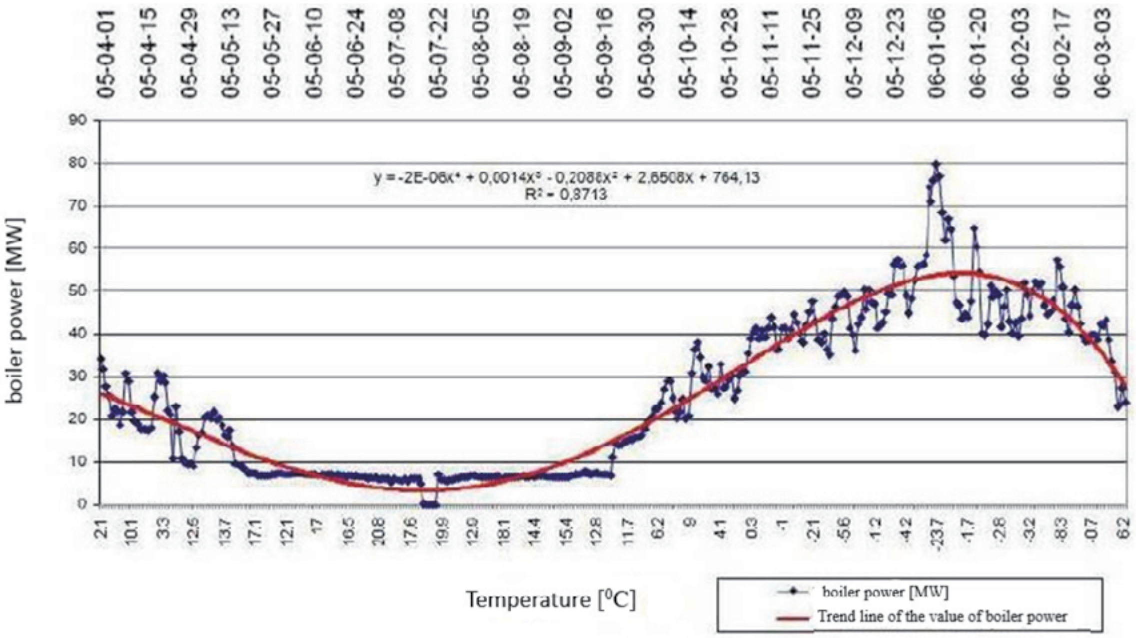

Fig. 2. Changes of boiler heating power vs. outdoor temperature in the period of one selected year for Heating Plant A (Różycka-Wrońska, 2016)

- maintain water circulation in the boiler until the fuel on the grate is completely burnt;
- burn off the fuel on the grate and remove slag from the grate to the slag hopper;
- stop the grate;
- turn off the fans.

Unstable work parameters of the furnace also occur in emergency situations. Unfortunately, boilers often have to work at changeable loads. Since there are as many as 769 WR boiler units in Poland, this is a serious problem.

The concentrations of pollutants in exhaust gas were determined for start-up and load change of the WR-25 boiler in Heating Plant A in two ways:

- with multiple regression, using STATISTICA statistical software,
- with linear regression complemented with the smart package in MATLAB.

Data for analysis were prepared in the following way:

- principal component analysis (PCA) was performed using the Kaiser and Cattell criterion (Różycka-Wrońska, 2016). The aim of PCA is to shift the coordinate system so as to maximize the variance of the first coordinate in the first place, and then the variance of the second coordinate etc.;
- the data were checked for normal distribution;
- outliers were rejected with the expert method (since these are experimental data, they are difficult to obtain and they are connected with boiler operation in unstable boiler work conditions, it is difficult to determine which data are wrong and which are real phenomena);
- point estimation of entry and exit data was used (data obtained from measurements were read every 2 seconds and data from monitoring were provided every 10 seconds).

Studies were done in Heating Plant A with a portable gas analyser GASMET DX-4000 manufactured by Envag in 2004, which uses the FT-IR measurement method, in accordance with the standard PN-ISO 10396:2001. The pollutant concentrations in the exhaust gas were measured during boiler operation in non-standard conditions (start-up, shutdown, load fluctuations). The calculation model installed in the computer connected to the measurement equipment produced the following data: the concentrations of SO_2, NO_x, N_2O, NO_2, NO, CO, NH_3, HCl, HF, CH_4. The measuring probe was placed in the channel behind the WR-25 boiler, the measurement cross-section was in accordance with the flow requirements for such measurements under Polish and EU standards: PN-ISO 10396:2001 and PN-EN 14181:2015-02. Figure 3 shows the location of the gas analyser probe during experimental measurements of the concentration of pollutants in the exhaust gases.

Elaboration of the methodology to determine pollutant concentrations in the exhaust gases entailed the development of a correlation relationship for conducting a simulation. The model needs to be verified before it can be regarded as true. The verification should be done by feeding the model with real data from other measurement days for start-up and shutdown. Such data are called verification data. The real data obtained from the heating plant concerned only compounds such as CO, NO_x, SO_2. These data were entered into the statistical packages MATLAB and STATISTICA.

Measurement samples were collected for start-up of the boiler WR-25 No. 1 and changing the load of boiler WR-25 No. 2 in a time interval of 2 s. After collecting the measurement data, the first step was to perform a linear regression analysis in STATISTICA during start-up in Heating Plant A. Data for compounds CO, NO_x, SO_2 were entered in the package.

The variable depended on the pollutant concentrations values of CO, NO_x, SO_2, and the forecast data, i.e., the data from the monitoring of the Heating Plant. The second step was to perform a linear regression analysis by analogy during the load change in Heating Plant A. Subsequently, verification data were entered in the existing statistical model.

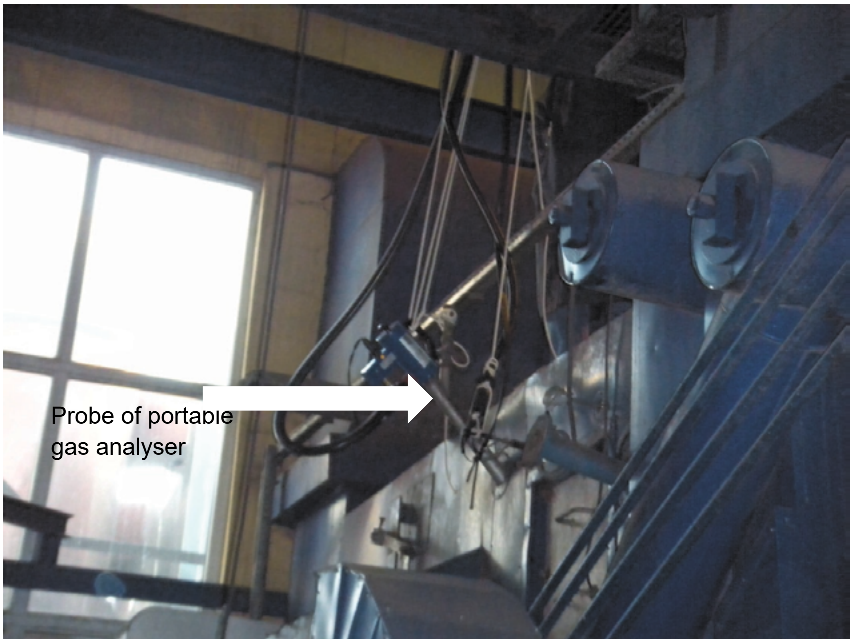

Fig. 3. Location of the gas analyser probe during experimental measurements of the concentration of pollutants in the exhaust gases

The verification data were obtained during start-up and shutdown of WR-25 type boiler no. 4. Boiler shutdown took place on 28 July 2013, start-up on 1 August 2013. The data were used to verify the proposed modelling with real values for start-up and shutdown in Heating Plant A.

The second statistical method uses linear regression enriched with a learner package in MATLAB. The MATLAB package used to model emissions is a universal matrix-based computing environment with real and complex elements, and all operations are operations on matrices and vectors (Hunt et al. 2002). This method includes the time window offset of the input, which affects the output. The coefficient determining the size of the time window at which the greatest correlation between the data occurs is corrSize = 8. With a larger time window there are too many degrees of freedom. In addition, the “learning” option (smart = true) is used which, based on the analysed data, improves the model by determining the highest correlation coefficient. This option was also helpful for creating a script that verifies the work of the proposed model based on other input and output data for start-up and shutdown. Based on the verification script, a calculation model was created for type WR-25 boilers for start-up and shutdown.

The compounds NO$_x$, CO, SO$_2$ are taken into account when determining the methodology for the pollutant concentrations in exhaust gases. The verification data were modelled in MATLAB. The data are based on identical sets of entry and exit data. Another start-up took place four days after boiler shutdown and was monitored with the same measurement system. Comparison of start-up and shutdown is done only for statistical modelling purposes, to describe physical phenomena.

Results

Measurements started at about 9:30 when Heating Plant A employees started up boiler no. 1. The results of measurements during boiler no. 1 start-up are presented in Fig. 4, 5 and 6. At 10:10, a rise in pollutant concentrations in the exhaust gas was observed, which is presented in Fig. 4. The highest level was noted for CO, over 700 mg/Nm^3 (N – stands for “normal” cubic meters, i.e., with the pressure of 101.325 kPa and temperature 0°C). Such major changes in CO concentration are primarily associated with the process of incomplete combustion. This frequently occurs when there is insufficient air for optimum combustion. The process stabilizes as the work of the furnace stabilizes. Appropriate division of air and fuel takes place when the boiler operates at nominal load – in normal conditions. As boiler efficiency and coal consumption volume went up, an increase in sulphur dioxide was observed. Due to increased efficiency and amount of coal burnt, the temperature rose in the combustion chamber, leading to generation of more NO$_x$, as is presented in Fig. 5. In turn, Fig. 6 shows the concentrations of compounds such as methane, hydrogen chloride and hydrogen fluoride, which are not covered by emissions limits from heat sources. The Regulation of the Polish Climate Minister of 24 September 2020 on emission standards for some types of installations, fuel combustion sources and waste incineration or co-incineration devices only sets limits of HCl and HF for waste incineration installations and some waste co-incineration installations. Average 24 h limits are 10 mg/Nm^3 for HCl and 1 mg/Nm^3 for HF, which is determined for 11% oxygen content in exhaust gases. As experimental studies show in Fig. 6, HCl and HF are also present in exhaust gases. Significant methane concentrations in the exhaust gas in the first stage of start-up prove there was an inadequate amount of oxygen provided to the furnace chamber. As furnace work slowly stabilized, CO and CH$_4$ levels went down. Around 13:15, conditions stabilized, the heating power of the boiler was 6.8 MW. For almost 2 hours, the conditions stabilized and reached values that were real for the given load. After the combustion conditions and heating load stabilized, the CO value was ca. 100 mg/Nm^3. At that stage of boiler operation, the limits of pollutant emissions determined in the Regulation of the Climate Minister were not exceeded. It should be stressed that operation of the WR-25 boiler at 7 MW is operation at low load (below 30% of the nominal load at which the boiler operates in stable conditions), which will still generate a stable amount of hazardous substances (SO$_2$, NO$_x$, HCl, HF, NH$_3$, CH$_4$, CO).

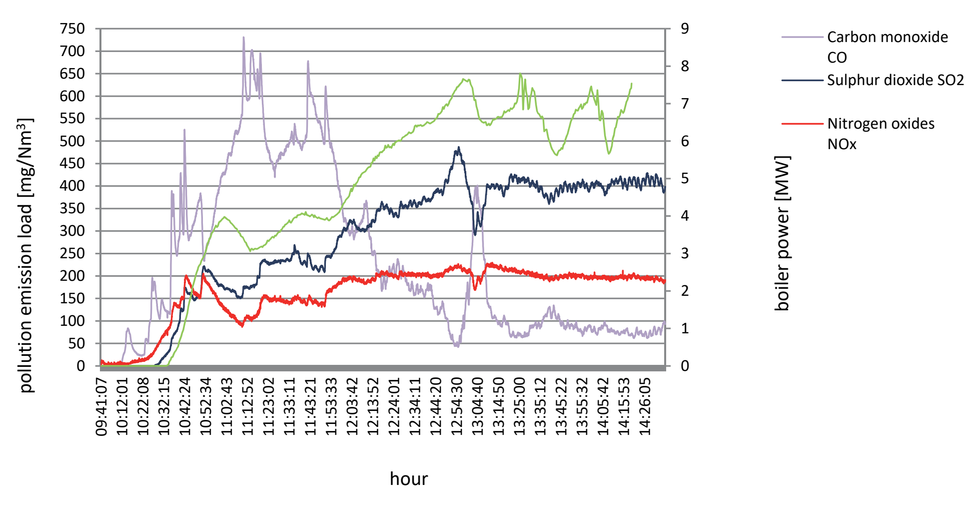

Fig. 4. Pollutant concentrations in the exhaust gases during boiler no. 1 start-up in Heating Plant A – compounds: CO, SO$_2$ and NO$_x$

The second stage of boiler operation – change of the heating load – was conducted in a different way. The measurement apparatus was connected to the exhaust channel behind the boiler and before the exhaust gas treatment unit, during boiler no. 2 operation. At that time the heating power was 6.95 MW. Stabilization of conditions lasted until ca. 12:30. Then, a change of load from 7 to 3 MW was started. With a WR-25 boiler, this is far below the acceptable load (7.5 MW) at which the boiler operates optimally with regard to the combustion process and emission of pollutants. As in the case of start-up, when the load decreased, there were greater CO concentrations in the exhaust gas. This rise was caused by insufficient oxygen in the furnace for complete combustion (Fig. 7). In this case the excess air coefficient was insufficient, leading to an excessive CO concentration in the exhaust gases. The fall in NO_x was connected with the lower temperature in the furnace chamber. Due to lower heat demand, the amount of supplied fuel went down. Therefore, lower SO_2 concentrations in the exhaust gas were observed. There was, however, a single peak, which probably shows momentary sulphur content in the combusted coal. After a short stabilization of parameters at the level of ca. 3 MW, there was a return to the entry load, which was reached at 14:10, as is shown in Fig. 7. Then the pollutant concentrations in the exhaust gases reached entry values. Fig. presents the concentrations of N_2O, NO and NO_2 in the exhaust gases during power changes of boiler no. 2 in Heating Plant A. Worrying levels of concentrations were noted for hydrogen fluoride (see Fig. 9), which at the beginning of the measurements had a stable value of ca. 12 mg/Nm^3 (allowable HF emissions in waste incineration plants are 1 mg/Nm^3). HCl concentrations in the exhaust gas fluctuated, depending on the load, as may be seen in Fig. 9. A few single peaks, as in the case of SO_2, may show temporary changes in chlorine content in the combusted coal. Since coal contains chlorine and fluorine compounds in its structure, the combusted sample likely had

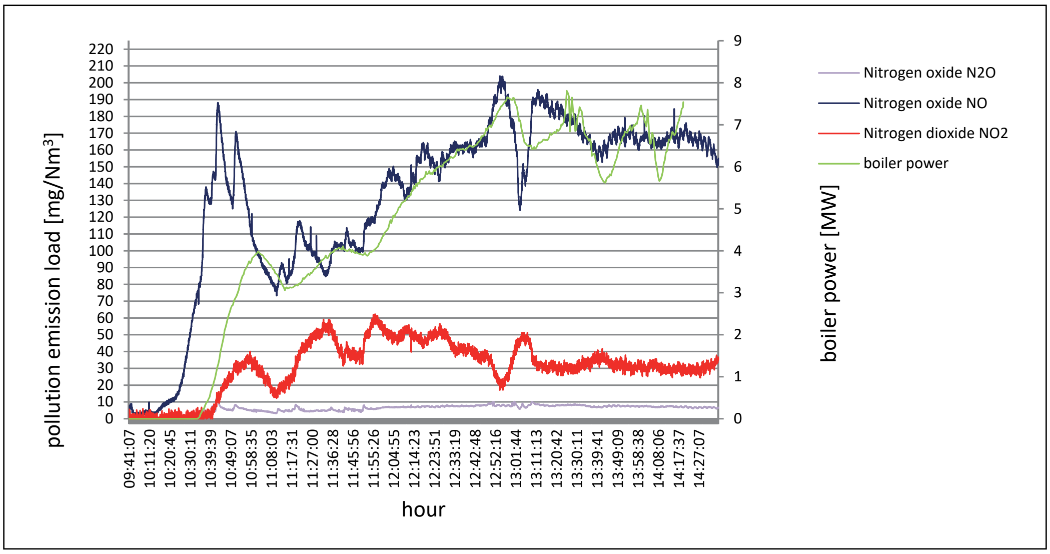

Fig. 5. Pollutant concentrations in the exhaust gases during boiler no. 1 start-up in Heating Plant A – nitrogen compounds: N_2O, NO and NO_2

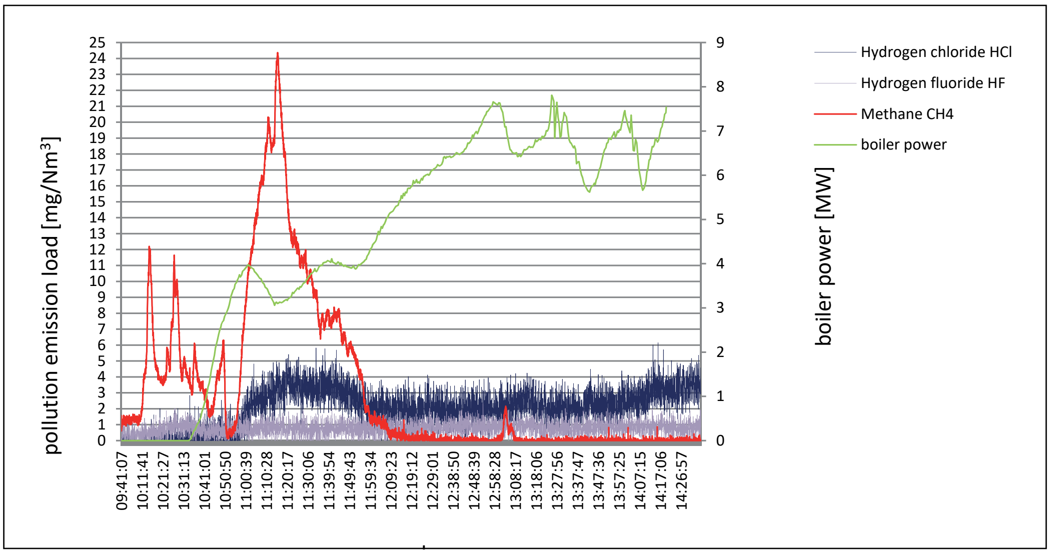

Fig. 6. Pollutant concentrations in the exhaust gases during boiler no. 1 start-up in Heating Plant A – compounds: hydrogen chloride, hydrogen fluoride, methane

a high content. Measurement results during boiler no. 2 load fluctuations are presented in Figs. 7, 8, 9.

The modelling resulted in determination of the Pearson linear correlation coefficient, Table 1 and Table 2.

In statistical studies, the values of the linear correlation coefficient only very rarely reach the values of -1, 0 or 1. When $|r_{xy}| > 0.9$, we have a very strong correlation between features X and Y. When $|r_{xy}| < 0.2$, it is usually stated that there is no correlation between the features. When r_{xy} ϵ [0.2, 0.9], then, depending on the number of sample elements, there is moderate, maybe significant correlation between the variables (Kukuła 1998).

A calculation model was developed in MATLAB and verified using appropriate data. The simulation model was prepared for the WR-25 boiler and it was created on the basis of experimental and verification data from Heating Plant A. The proposed optimization model did not work in the case of verification of CO concentrations in the exhaust gas. This could be the result of a large discrepancy in the character of changes in verification data, the values of which diverged significantly from the concentration values in the experimental data. Moreover, verification of the boiler start-up modelling for NO_x concentrations in the exhaust gas did not meet expectations. The start-up was likely conducted in another way and the character of temperature changes in the combustion chamber differed significantly, which directly impacted the NO_x concentrations in the exhaust gas.

In STATISTICA, the proposed model adapted well to the data. The only discrepancy was with CO concentrations in the exhaust gas, which did not reach a correlation coefficient of

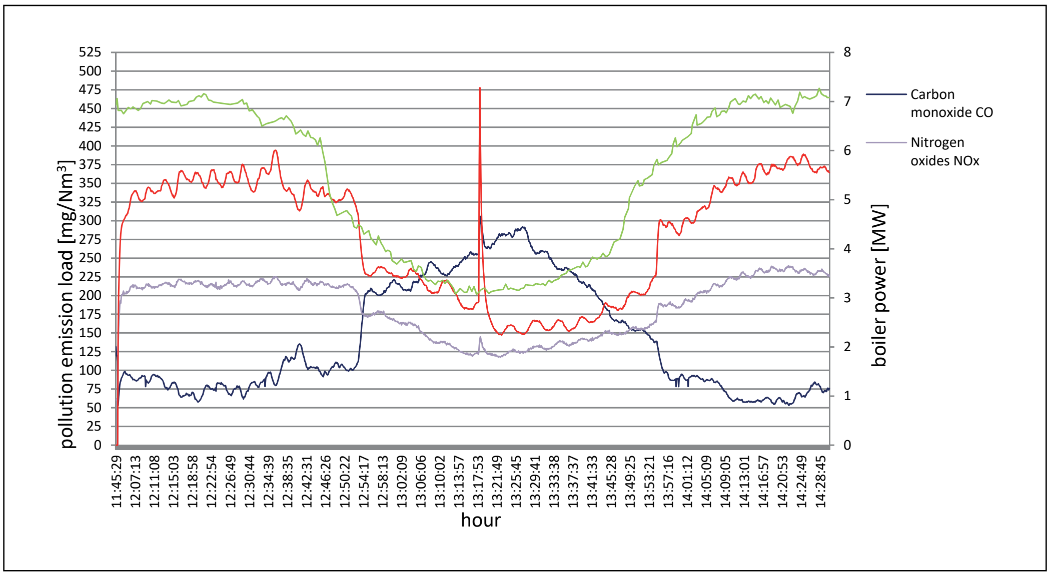

Fig. 7. Pollutant concentrations in the exhaust gases during power changes of boiler no. 2 in Heating Plant A – compounds: CO, SO_2 and NO_x

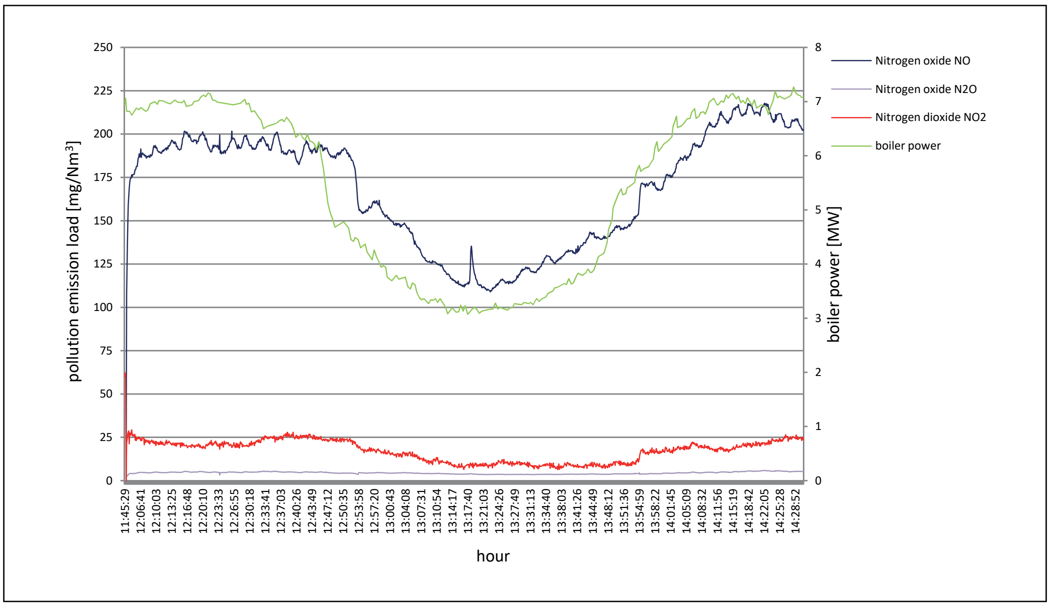

Fig. 8. Pollutant concentrations in the exhaust gases during power changes of boiler no. 2 in Heating Plant A – nitrogen compounds: N_2O, NO and NO_2

above 50%. However, the proposed statistical model may be used in optimization analyses of WR-25 boilers for start-up and shutdown.

Discussion

The experimental studies conducted confirm the thesis that pollutant concentrations in exhaust gases rise significantly when boilers are operated in non-standard conditions. During the summer, boilers operate at lower load, below 30% of the nominal load at which their work is stable. This causes greater pollutant emissions to the atmosphere. This is a widespread problem in Poland, which has 769 WR boiler units and over 300 OR steam boiler units of practically identical design. Each boiler unit is started up and shut down on average six times a year. This gives 4,614 start-ups and the same number of shutdowns of boiler units per year. When we add to this the period outside the heating season, the issue of increased pollutant emissions becomes very serious.

Summing up, when designing a boiler house, one should take into account heat load fluctuations and design, and select boiler units so that they operate at maximum efficiency for as much of the year as possible. During maintenance, one should select the cooperation of such a number of boiler units as to achieve a load that is close to nominal load, where maximum efficiency occurs. Each boiler in the heating plant should be loaded evenly. This problem particularly impacts heating plants which have only WR-25 boilers. Here the problem of low loads is present especially in the summer, when the heating plant operates only for hot consumable water purposes. To give an example: in Heating Plant A in 2012 WR-25 boiler no. 1 in the heating season worked for 59 days with a load below 30% of the nominal power; it was started up and shut down three times and for the whole time outside of the heating season it

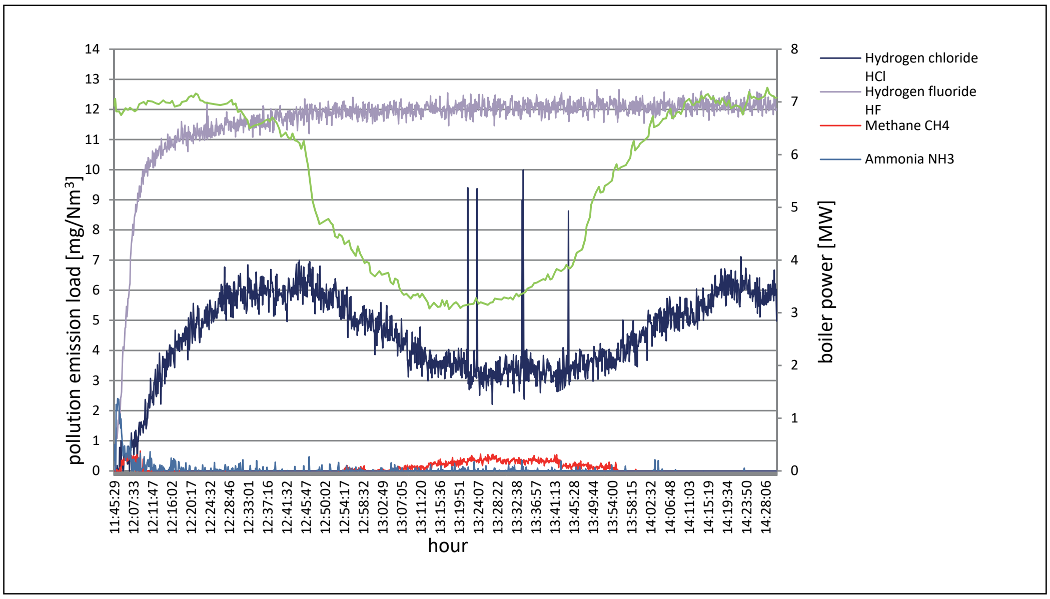

Fig. 9. Pollutant concentrations in the exhaust gases during power changes of boiler no. 2 in Heating Plant A – compounds: hydrogen chlorine, hydrogen fluoride, methane, ammonia

Table 1. Pearson linear correlation coefficient for start-up and load change of WR-25 boiler no. 4 in Heating Plant A

	STATISTICA			MATLAB		
Pearson correlation coefficient – start-up	0.77	0.99	0.93	0.81	0.99	0.93
Pearson correlation coefficient – load change	0.98	0.96	0.98	0.97	0.97	0.99

Table 2. Pearson linear correlation coefficient determined after model verification for start-up and shutdown of WR-25 boiler no. 4 in Heating Plant A

	STATISTICA			MATLAB		
	CO	SO_2	NO_x	CO	SO_2	NO_x
Pearson correlation coefficient – verification data for start-up	0.01	0.85	0.56	0.11	0.54	0.02
Pearson correlation coefficient – verification data for shutdown	0.30	0.82	0.79	0.37	0.80	0.79

operated at below nominal load. This gives 516 working hours per year with a much higher unit emissions of pollutants, and that is neglecting the start-up and shutdown periods.

Analyzing the results of the conducted experimental studies, an installation of CHP with gas engines is proposed, operating for hot consumable water purposes. Combustion of natural gas does not lead to the creation of sulphur oxides. CO_2 and NO_x emissions in CHP units are 20–60% lower than in coal-fired units. The additional advantage of being able to generate electricity and reduce total pollutant emissions to the atmosphere plays an important role in view of increasing requirements in the district heating sector. Similar studies connected with LCA were done by Maurice B., et al., 2000, determining the impact of CO_2 equivalent emissions during electricity production from coal. Directions of changes were shown in order to limit emissions and change fuel parameters (Maurice et al 2000, Andersen and Lund 2007).

One should also pay attention to the boiler start-up and shutdown process itself. It must be done in accordance with the manufacturer's guidelines, boiler characteristics, materials used and construction. The person supervising the boiler during its operation must strictly follow the appropriate procedures. These are conditions where the installation does not operate at full load, which causes: lower energy efficiency, inefficient dust removal from flue gases, increased fuel consumption and unstable furnace working parameters. To best prevent damage to structural elements of the boiler, these processes should be done very slowly. The lining in the furnace chamber should not be exposed to rapid temperature change, nor should any other structural elements. How fuel is supplied to the mechanical grate is also important. Heat conductivity efficiency determines ignition of coal on the grate, so good transport will enable ignition of even poorer quality coal. It will also move the flame away from the ceiling and combust coal on a larger area of the grate, thereby reducing NO_x emissions caused by an overheated ceiling. Start-up time strictly depends on the size of the boiler unit.

The Polish DH sector has great potential in terms of improving fuel consumption efficiency and cutting emissions of pollutants to the atmosphere. The heat generating plants, i.e., CHP or HOB plants for this sector used ca. 10,000,000 Mg of hard coal for heat generation and emitted 106.6 Mg of CO_2, 0.39 Mg of SO_2, 0.18 Mg of NO_x and 0.07 Mg of particulate matter per each TJ of generated heat. Average heat generation efficiency was 84%. Increasing the efficiency by 1 percent point would decrease fuel consumption annually by ca. 100,000 Mg. CO_2 emissions would then go down by ca. 1,000 kg, SO_2 by ca. 4 kg, NO_x by ca. 2 kg, and particulate matter by ca. 1 kg per 1 TJ of generated heat.

This provides an excellent basis for promoting cogeneration with CHP gas systems, which would operate in heating plants in summer as the basic process and in the heating season could, in addition to electricity production, take over the function of peak boilers for heat generation, thereby balancing the loads of coal-fired boilers.

Conclusions

An optimization model was developed for boilers operating in unstable conditions, which is valid for all makes of WR-25 boiler. Model trends are quality trends. Fluctuations in pollutant emission loads can be observed, but the model is not accurate enough to determine the precise values of these fluctuations. Certain similarities are evident when one compares the two modelling studies that were conducted. In both cases, the modelling of pollutant emission loads in respect of CO failed to match verification data. This might be caused by significant divergence in the character of changes in the verification data. However, the proposed model provides a basis for optimizing combustion processes for WR boilers in unstable operating conditions i.e. start-up and shutdown.

A correlation relationship was developed which was used in the simulation of pollutant emissions in unstable boiler operating conditions and, in future analysis, it may be used to calculate annual pollutant emissions to the atmosphere in changeable operating conditions.

The experimental studies also measured concentrations of compounds in exhaust gases that are not yet covered by emission limits. These compounds are HCl, CH_4, HF, NH_3. Hydrogen chloride and hydrogen fluoride are monitored in waste incineration plants, which leads us to believe that concentrations of these substances in the air above the admissible limits are hazardous for human health and the environment. This gives rise to an evident need for in-depth analysis of the impact of the measured substances on human life and health, as well as the introduction of emissions limits for these substances.

This paper does not conclude the research that could be done to further analyze pollutant concentrations in exhaust gases during boiler operation in unstable conditions. Future research should encompass more experimental studies, detailed analysis of parameters of combusted coal, and analysis of the course of start-ups and shutdowns of boiler units, in particular heating plants. The optimization model developed on the basis of statistical packages could be included in a controller and work in real time, corrected with real time measurements.

Conflict of interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

Founding

This paper was co-financed under the research grant of the Warsaw University of Technology supporting scientific activity in the discipline of Environmental Engineering, Mining and Energy.

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Eksploatacyjne uwarunkowania emisji zanieczyszczeń gazowych z węglowych źródeł ciepłowniczych

Streszczenie: Prezentowana praca badawcza opisuje korelację między emisją gazowych zanieczyszczeń powietrza do atmosfery, a parametrami spalania dla wodnego kotła rusztowego opalanego węglem typu WR-25, o mocy cieplnej 25 MW w niestabilnych warunkach pracy, takich jak: rozruch, odstawianie z ruchu i praca przy obciążenia poniżej minimum technicznego. Przedstawione analizy opierały się na własnych pomiarach autorów wykonanych dla kotłów rusztowych typu WR zasilających w ciepło miejskie systemy ciepłownicze oraz na wynikach z symulacji komputerowych wykorzystujących uzyskane dane pomiarowe. Autorzy prezentują, wskaźniki emisji zanieczyszczeń gazowych do atmosfery, w oparciu o pomiary tych emisji w niestabilnych warunkach pracy kotła typu WR, a których to wskaźników aktualnie brakuje zarówno w literaturze jak i praktyce inżynierii ochrony atmosfery. Wskaźniki te pozwolą na rzeczywiste oszacowanie wielkości emisji gazowych zanieczyszczeń do atmosfery w takich niestabilnych warunkach pracy kotła, jak również ich wpływ na jakość powietrza w otoczeniu. Prezentowana praca dostarcza modele obliczeniowe do identyfikacji obciążenia emisyjnego zanieczyszczeniami gazowymi do atmosfery w jakichkolwiek, a przede wszystkim w niestabilnych warunkach pracy kotłów typu WR-25.