Emission of Air Pollutants in the Hot Water Production

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Abstract. The result of the deteriorating condition of the environment and climate change is to increase the efficient use of fuel and energy and the rational use of energy resources. Great potential for reducing consumption of fossil fuels are stuck in heating systems ranging from generation, transmission and distribution and ending with the recipients rationalize their consumption of heat. Efficient production of heat is obtained during optimal boiler load. The boiler type WR operates with the highest efficiency of 80-85%, the rate of fuel consumption is the lowest, and the process is close to complete combustion. In such conditions to the atmosphere are emitted mainly: SO₂, CO₂ and NOₓ. Pollutants such as CO, CH₄, HF, HCl, NH₃, etc., are the result of incomplete and imperfect combustion, that is, when the boiler is working inefficiently [1-3]. Measurements of pollutant concentrations were performed using an analyzer FTIR Gasmet DX4000. Fourier Transform Infrared Spectroscopy is a technique of measuring that allows a very precise identification of qualitative and quantitative range of compounds, including gaseous pollutants. Device used to measure the concentrations of gaseous pollutants allow determining the amount of carbon, sulphur and nitrogen compounds, which measurement is not defined any rules, including chlorine compounds, hydrogen, methane, ammonia and volatile organic compounds. In this publication presents part of the literature the use of heat for domestic hot water production in summer and heating demand in winter. Described the characteristics of the water boilers WR type used for heating. Presents the results study of the emissions in the production of hot water for the summer and winter seasons.

1. Introduction
Heat from municipal heat distribution networks is a widely known product; however, a substantial majority of consumers use it only in the winter season. Consumers using network heat for heating purposes do not realize that the product may be used outside the heating season as an all-year-round source of hot tap water. Such situation results from the fact that years ago the plans to provide consumers with network heat did not consider provision of the product in the summer period, which contributed to application of individual gas heaters in residential buildings. Unfortunately, using simplest gas heaters is a source of many problems and the most serious is connected with safety of users [4, 5]. In old buildings one of elements which assured proper ventilation of such buildings were draughty windows. Their replacement made in order to increase energy efficiency and to improve aesthetic qualities has disturbed the operation of gravitational ventilation systems. In the heating period there may be not enough air necessary to totally combust gas. A lack of chimney draughts results in the situation in which products of combustion remain in flats, thus, posing a deadly threat for
inhabitants. Attempts to reduce the threat may be made by fixing window ventilators or carbon monoxide detectors; however, that is connected with periodical inspections and services [4, 5].

For security reasons and due to dynamic changes in prices of energy carriers, inhabitants are more willing to search for cheaper, safer and more comfortable solutions. One of them is heat from a heat distribution network. A supply of centrally prepared water with a constant temperature to all draw-off points of the building is possible thanks to simple installation techniques, without the necessity to carry out extensive renovations. In buildings connected to the heat distribution network, it is required to replace the present individual single-function heating substation into a two-function compact heating substation (central heating and hot tap water) or to extend the sub-station to add a module responsible for heating water. Moreover, a hot water system should be built to supply hot water from the exchange centre to flats of users. The last step is disassembly of individual water heaters. In special cases, alternation of the existing heat distribution network is necessary. Such situation may take place when the existing high-parameter connection is not sufficient to supply additional thermal power for preparing hot tap water [5-7].

![Block diagram of heat distribution network.](image)

The notion of a heat distribution network means a set of technical devices serving for transport of heat from the heat source to consumers via a heat carrier with adequate parameters. A block diagram of heat distribution for a typical heat distribution network was presented in figure 1. The first element of a heat distribution network is heat generating plants and heat and power generating plants. A heat generating plant forms a set of devices in which as a result of fuel combustion a heat carrier of a required temperature and pressure is created for the needs of the heat distribution system. In a heat and power generating plant, electric energy and heat are produced in cogeneration. Transmission and distribution of heat directly to the end user or through co-housing operatives are effected by power engineering companies [4, 7-10].

2. WR water boilers in heat engineering
WR water boilers are typical boilers still popular in professional, industrial and utility heat-generating plants. They meet the demand for heat and their basic fuel is bituminous coal. They have a simple structure, are reliable, easy to operate, fulfil current requirements of Polish environmental protection standards concerning low emission of pollutants and they have a relatively high dynamics and a low demand for electric energy of auxiliary devices. WR water boilers achieve efficiency of more than 85% when using from 30% to 100% of its nominal power. Combustion of solid fuels in WR stoker-fired boilers ensures great stability, especially for boilers in which fuel and air are fed counter-currently [2, 3, 6, 11-16].

A diagram of a demonstration heat-generating plant with a section of WR boiler were presented in fig. 2. Bituminous coal from dumps called coal grounds is transported through conveyor belts to a boiler bunker. Then, the fuel gets to the grate where it is heated, dried and carbonized, and after it reaches the direct combustion zone, the process of gasification and oxidation occurs [1, 11-13, 17-19].
Combustion gases which are created in the process of energy conversion get first to cyclones in which the process of gas extraction takes place, and then to the chimney.

![Figure 2. Diagram of heat-generating plant [6]:](image)

1-furnace chamber, 2–grate, 3–grate drive, 4–rotary vane feeder, 5–boiler bunker, 6 I feedwater heater bank, 7–II feedwater heater bank, 8–feedwater heaters, 9–discharge water temperature detector, 10–entering water temperature detector, 11–flowmeter, 12–air flow fan, 13–heated water spout, 14–cold water inflow, 15–boiler control unit, 16–GASMET DX-4000 analyzer sampling probe, 17–J.U.M. OVF 3000 analyzer sampling probe, 18–GASMET DX-4000 analyzer, 19–J.U.M. OVF 3000 analyzer, 20–computer, 21–gas extractor–cyclone, 22–chimney, 23–belt conveyor, 24–bituminous coal yard.

The amount of coal, its type and quality have a direct influence on the boiler operation, efficiency, combustion process and, consequently, emission of pollutants. Moreover, the type and amount of pollutants emitted to the atmosphere depend mainly on boiler operation. During normal operation, i.e. operation with nominal power of the boiler, the main products of combustion are dusts, CO₂, SO₂ and NOₓ. In abnormal conditions, i.e. during incomplete or imperfect combustion, additionally, pollutants such as CO, HF, HCl, CH₄, NH₃ and VOC are created [13, 3, 20-23].

A unitary change of pollutant emission factor is also affected by a changeable load of the boiler which depends on weather conditions. There are two seasons: summer season and heating season. In the summer season, outside the heating season, a heat-generating plant operates mainly on the basis of boilers producing hot tap water, using approximately 10-30% of its nominal power. In the heating season, a heat-generating plant covers the demand for heat for heating purposes and production of hot tap water, thus, reaching its nominal power [2, 11, 13, 16, 22, 23].

3. Research into emission of pollutants in the process of hot water production in summer and winter seasons.

Research into emission of pollutants in the process of hot water production was carried out in a municipal heat-generating plant located in the Sub-Carpathian Province. A WR10 stocker-fired water boiler was examined. A diagram of the boiler room in which measures were made was presented in figure 2. An analysis of the composition of combustion gases was conducted in a continuous way on a section behind the boiler in specially prepared measuring holes.

Establishing parameters of boiler operation and concentration of pollutants in exhaust gases required special measuring conditions. Ideal conditions would be to keep a steady state, i.e. to keep the thermal balance equation:

\[
\dot{Q} = \dot{Q}_u + \dot{Q}_w + \dot{Q}_n + \dot{Q}_{CO} + \dot{Q}_z + \dot{Q}_r
\]  

(1)
where: $\tilde{Q}_w$ – effective thermal power transferred to water, $\tilde{Q}_w$ – thermal power carried away to the surrounding with combustion gases (carry-over loss), $\tilde{Q}_r$ – thermal power of incomplete combustion losses, $\tilde{Q}_{CO}$ – thermal power of imperfect combustion losses, $\tilde{Q}_z$ – thermal power of hot slag losses, $\tilde{Q}_r$ – thermal power of losses to the surrounding air through convection and radiation.

Keeping the steady state means the assurance of stability of all parameters during the measuring period. It is possible when a constant flow of the heated factor, air and fuel fed for combustion is maintained. Conditions of boiler operation, mainly the temperature pattern, is established after several hours. In fact, keeping such state would be difficult. The boiler room operated with a load which is variable in time, covering an instantaneous demand of users for heat. Therefore, measures were conducted continuously for 30 min., in which the boiler operated with a constant load. It was assumed that the analysis of measurement results would have a confidence interval of 95%.

The measurement of combustion gas composition was carried out using a multi-parameter GASMET DX-4000 analyser of combustion gases [24]. The device enables to perform automatic measurements of volume fractions of the following compounds: H$_2$O, CO$_2$, CO, NO$_x$, SO$_2$, NH$_3$, HF, HCl, CH$_4$, O$_2$. The speed of flow and temperature of combustion gases were measured using a HD2134P.2 micromanometer. The calculated emissions are a product of received concentrations of pollutants, the speed of combustion gas flow and geometrical dimensions of the flue.

Table 1 presents average parameter results of boiler operation in the summer and winter seasons from 30-minute measurement. Boiler power depended on the instantaneous demand for heat and was 0.5MW for the summer season and 5.5MW for the winter season.

| Season | Boiler power, MW | Boiler efficiency,% | Temperature of combustion gases, °C | Combustion gas flow, m$^3$/s | Content of O$_2$ in combustion gases,% |
|--------|-----------------|---------------------|------------------------------------|-------------------------------|-------------------------------------|
| Summer | 0.5             | 26                  | 92                                 | 13.2                          | 19.86                               |
| Winter | 5.5             | 67                  | 129                                | 15.36                         | 9.86                                |

Table 2 presents calculated emissions of pollutants in the process of hot water production in the summer and winter seasons. To better illustrate the results, emissions per 1 kWh of produced heat were also calculated.

| Pollutant | Emission in the season: | Emission per 1kWh in the season: |
|-----------|--------------------------|----------------------------------|
|           | Summer | Winter | Summer | Winter |
| CO$_2$, % | 1.93   | 8.30   | -      | -      |
| CO, mg/s  | 5215.47 | 4454.40 | 10430.94 | 809.89 |
| NO$_x$, mg/s | 539.40 | 3175.37 | 1078.81 | 577.34 |
| SO$_2$, mg/s | 2326.50 | 12823.14 | 4653.00 | 2331.48 |
| NH$_3$, mg/s | 1.23 | 3.99 | 2.46 | 0.73 |
| HCl, mg/s | 214.57 | 1628.77 | 429.14 | 296.14 |
| HF, mg/s | 9.89 | 35.33 | 19.78 | 6.42 |
| CH$_4$, mg/s | 52.94 | 0.00 | 105.88 | 0.00 |

Figures 3 to 10 present emissions of specific pollutants in a graphic form. White bars indicate actual emission in the summer and winter season. Gray bars indicate pollutant emission per 1kWh.
3.1. CO emission

Figure 3 presents a chart of CO emission in the process of hot water production and CO emission per 1 kWh of produced heat. Carbon monoxide is a strongly poisonous gas and it is created as a result of imperfect combustion. In the summer season, the emission is 5 215 mg/s, and 10 431 mg/s per 1 kWh of heat. In the heating season, the emissions are 4 454 mg/s and 810 mg/s, respectively.

![Figure 3](image.png)

**Figure 3.** Chart of CO emission in the process of hot water production expressed in mg/s and mg/s per 1 kWh of heat in different seasons in a year.

3.2. NOX emission

During combustion of fossil fuels, most nitric oxides are created in a form of nitric oxide with a small participation of nitric dioxide. A mixture of these compounds are known as NOX and it constitutes more than 90% of nitric oxides created in the process of fossil fuel combustion [2, 25]. A harmful influence of NO on the environment and human health results from their direct effect, and indirect effect from creation of photochemical oxidizers which are a component of smog [2, 26]. Figure 4 presents a chart of NOX emission. In the summer season, the emission is 539 mg/s, and 1 079 mg/s per 1 kWh of heat. In the heating season, the emissions are 3 175 mg/s and 577 mg/s, respectively.

![Figure 4](image.png)

**Figure 4.** Chart of NOX emission in the process of hot water production expressed in mg/s and mg/s per 1 kWh of heat in different seasons in a year.

3.3. SO2 emission

Sulphur monoxides are created mainly during combustion of sulphur contained in fuel itself. Most sulphur monoxides created in the process of combustion form SO2. It is harmful both for the environment and for humans. It reacts with water vapour contained in the air and, consequently, it is the main cause of acid rains. Along with NOX, it is a component of smog [21, 26]. Figure 5 presents a chart of SO2 emission. In the summer season, the emission is 2 327 mg/s, and 4 653 mg/s per 1 kWh of heat. In the heating season, the emissions are 3 175 mg/s and 577 mg/s, respectively.

![Figure 5](image.png)
3.4. NH\textsubscript{3} emission

Figure 6 presents a chart of NH\textsubscript{3} emission. In the summer season, NH\textsubscript{3} emission is 1.23 mg/s, and 2.46 mg/s per 1 kWh of heat. In the heating season, the emissions are 3.99 mg/s and 0.73 mg/s, respectively.

3.5. HCl emission

The main reason for creation of hydrogen chloride is a content of chlorine in fuel in a form of inorganic salts (chlorides) and in a form of chloro derivatives. Chlorine compounds contained in combustion gases have a negative influence on the environment as a component of acid rains and are an additional corrosion factor for boiler and flue elements [27]. Figure 7 presents a chart of HCl emission. In the summer the emission is 214.57 mg/s, and 429.14 mg/s per 1 kWh of heat. In the heating season, the emissions are 1628.77 mg/s and 296.14 mg/s, respectively.

Figure 5. Chart of SO\textsubscript{2} emission in the process of hot water production expressed in mg/s and mg/s per 1kWh of heat in different seasons in a year.

Figure 6. Chart of NH\textsubscript{3} emission in the process of hot water production expressed in mg/s and mg/s per 1kWh of heat in different seasons in a year.

Figure 7. Chart of HCl emission in the process of hot water production expressed in mg/s and mg/s per 1kWh of heat in different seasons in a year.
3.6. HF emission

Just like chlorine, fluoride is a natural element occurring in fossil fuels. In the combustion process it combines with hydrogen creating hydrogen fluoride and with the participation of moisture in the air it is transformed into the form of hydrofluoric acid [28]. Figure 8 presents a chart of HF emission. In the summer season, the emission is 9.89 mg/s, and 19.78 mg/s per 1 kWh of heat. In the winter season, the emissions are 35.33 mg/s and 6.42 mg/s, respectively.

Figure 8. Chart of HF emission in the process of hot water production expressed in mg/s and mg/s per 1 kWh of heat in different seasons in a year.

3.7. CH4 emission

Just like carbon dioxide, methane belongs to the group of greenhouse gases; also, to a certain degree, its participation causes degradation of the ozone layer. Figure 9 presents a chart of CH4 emission. In the summer season the emission is 52.94 mg/s, and 105.88 mg/s per 1 kWh of heat. In the winter season measuring equipment did not detect methane in the composition of combustion gases.

Figure 9. Chart of CH4 emission in the process of hot water production expressed in mg/s and mg/s per 1 kWh of heat in different seasons in a year.

3.8. CO2 concentrations

Carbon dioxide is created as a result of full combustion (oxidation) of coal. It belongs to the group of greenhouse gases. It is estimated that during combustion of solid fuels, its emission in 2016 was 284863.92 kt. Figure 10 presents a chart of CO2 concentrations in combustion gases. In the summer season, the emission was 1.81% and in the winter season it was 7.68%.
4. Conclusions

Variability of the load of heat-generating plants depends on external air temperature and, therefore, covering the demand for heat requires highly flexible operation of boilers. In summer and winter seasons, an average daily demand for hot tap water is constant. In the heating season, a demand for heat increases by needs for central heating which is different and strongly correlated with temperatures in the given period. Effective heat production with minimum consumption of fuel and stable parameters of boiler operation and of the dust extraction system are obtained with optimal boiler loads, i.e. at 85-95% of its nominal power. Operating under such conditions, a WR boiler obtains highest designed efficiency at 80-85%. Additionally, the lowest fuel consumption rate is achieved then, which is a result of almost complete and perfect combustion and the lowest pollutant emission factor per unit of produced heat. Keeping such parameters results mainly in emission of dust, SO$_2$, CO$_2$ and NO$_X$. Other pollutants, especially CO, CH$_4$, HF, HCl, NH$_3$ and other, are an effect of incomplete and imperfect combustion.

On the basis of performed measurements of concentrations and determined pollutant emissions, expected changes in emissions of specific pollutants were achieved in the heat-generating plant equipped with a WR10 water boiler. In the winter season, the boiler operated with a load smaller than its nominal power, i.e. 5.5 MW. High SO$_2$, NO$_X$ and CO$_2$ emissions indicate an almost complete and perfect combustion process. Also, a higher level of HF and HCl emission compared to the summer season was observed, which may result directly from the content of fluoride and chlorine in fuel. In the summer season, the minimum load of the boiler (0.5 MW), efficiency (26%) and emission of specific pollutants indicate a process of incomplete and imperfect combustion. A significantly higher level of CO and CH$_4$ emission was observed. Moreover, higher emissions of all pollutants per 1 kWh of produced heat were obtained in the summer season.

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Figure 10. Chart of CO$_2$ concentration in the process of hot water production expressed in % in different seasons in the year.
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