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Analysis of the possibility of identifying incorrect operation of heating devices in real conditions

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Abstract. The paper presents a preliminary stage of works aiming at a development of a method of identification of a wrong use of heating equipment under actual conditions of operation based on an a continuous analysis of oxygen level in the exhaust gas. The investigations were carried out on a test stand at the Chair of Thermal Engineering of Poznan University of Technology. For the tests, the author used a Q-EKO 15 boiler by Heiztechnik available in the Polish and European markets. In order to develop the method of identification of a wrong use of the boiler, the investigations were divided into two stages. In the first stage, the boiler was tested according to the PN-EN 303-5 standard using the manufacturer-recommended fuel. In the second stage of the investigations, an experiment was performed simulating a wrong use of the boiler burning waste material under actual conditions of operation. To this end, generally applied modifications in the boiler design were performed allowing the use of waste material as fuel. During the tests, the amount of oxygen O_2 in the exhaust gas was monitored. It was observed that even slight attempt to operate the boiler incorrectly could be detected based on the analysis of the oxygen level in the exhaust gas.

1 Introduction

The Clean air is extremely important in maintaining the quality of life. Polluted air significantly influences human health causing a variety of conditions of the blood and respiratory systems. In urbanized and industrialized regions, one may observe the greatest impact of polluted air on human and animal health. The assessment of the air quality is performed based on the measurement of its pollution with sulfur dioxide, carbon monoxide, nitrogen dioxide, PM10 and PM2.5 particulates. According to the WHO report, As many as 7 Polish cities are in the top ten having the highest air pollution [1].

Pursuant to Art. 25b of the Environment Inspection Act dated 20 July 1991 (Journal of Laws 2013 r., item 686, as amended) [2], Every 4 years, General Inspector of Environment Protection prepares a report on the condition of the environment in Poland [3]. In the last report of 2014 it was specified how big the impact of the housing sector was on the

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environment. Figure 1 indicates that the housing sector is the main source of particulate matter. In 2012 the amount of emitted PM was approx. 250 thousand tons per year.

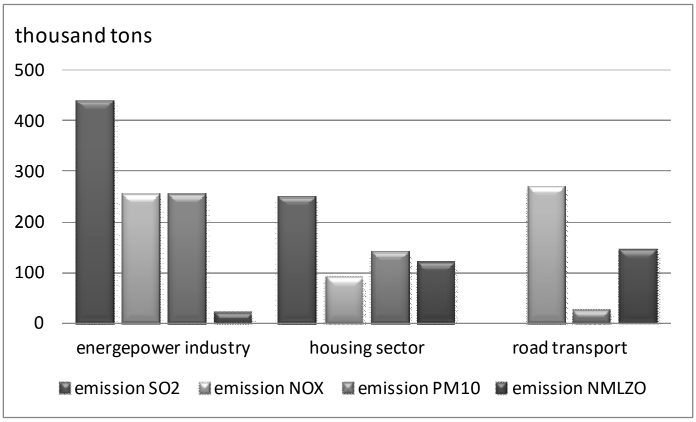

Fig. 1. The structure of emissions of the main pollutants in Poland in 2012 as divided into economy sectors [3]

The main reason for such high pollution is the wrong use of the heating equipment in the households. Improved technology of solid fuel boilers used in the housing sector allows an increasingly more efficient and low emission combustion. As per standard [4] solid fuel boilers of the power output lower than 50 kW, in the environment class 5, have their exhaust emissions limited to 500 mg/m^3 for CO and 40 mg/m^3 for the PM at 10% O_2. These values show how low the emission can possibly be when employing contemporary technology. The basis for the advancement of modern, low temperature solid fuel water boilers is the innovative design solutions. The condition for the obtainment of low emission level is the proper use/operation of the equipment as well as the use of the manufacturer-recommended fuel. Unfortunately, low environment awareness of the society and the lack of inevitability of punishment result in the fact that users of heating systems fuel their boilers with waste material.

The paper presents the first stage of the works aiming at a development of a method of identification of a wrong use of heating equipment under actual conditions of operation based on a continuous monitoring of oxygen level in the exhaust gas. The proposed method is unique on a world scale.

2 Design of the measurement stand

In order to develop the method of identification of a wrong use of the heating equipment under actual conditions of operation, the author carried out investigations on a specially designed measurement stand located on the premises of Poznan University of Technology. In the test, the author used an EKO 15 steel boiler manufactured by Heiztechnik. It is a low power output boiler designed for heating of buildings of the heat demand up to 75 kW coupled with hot domestic water storage tank. Figure 2 presents the schematics of the Q-EKO series boiler fitted with a feed system, a retort burner and a blower fan [5].

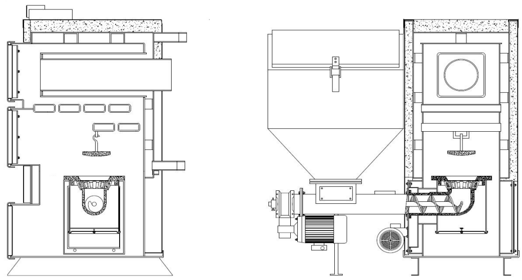

Fig. 2. Schematics of the Q-EKO series boiler [6]

The rated power output of the boiler, as declared by the manufacturer, is 15 kW. In order to control the boiler, PID system was applied using the proportional integral derivative (PID) algorithm operating based on the data fed from the exhaust gas analyzer. Figure 3 shows the schematics of the measurement stand.

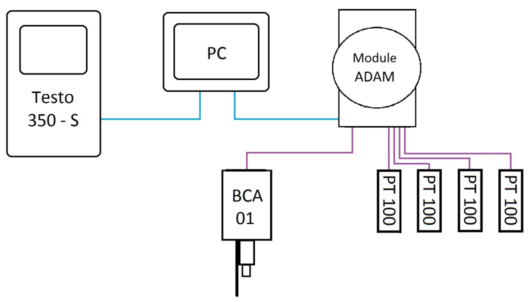

Fig. 3. Schematics of the measurement stand

The first section of the measurement stand is composed of the Testo 350 -S exhaust gas analyzer connected directly to the computer system through a USB port. The analyzer is based on the Testo Easy Emission software allowing a direct measurement and recording of all the measurement results. The second section of the stand utilizes ADVENTECH ADAM 4000 series modules [7]. In order to record the measurements, AdamView software was applied carrying out the recording of the data received from the PT100 temperature sensors and the BCA-01 measurement probe (shown in Fig. 4) using appropriate measurement procedures.

Fig. 4. BCA-01 analyzer [8]

The advantage of the BCA-01 Brager analyzer is the possibility of performing continuous measurements of the following physical and chemical quantities:

- % oxygen (O_2) concentration in the exhaust gas (from 0 to 21 %),
- Excess air coefficient [λ],
- % carbon dioxide (CO_2) concentration,
- exhaust gas temperature,
- intake air temperature,
- heat loss.

The measurement stand was designed according to the applicable PN-EN 303-5 standard.

The above configuration allowed recording of the following parameters:

- water outlet temperature, T_z [°C],
- return water temperature, T_p [°C],
- water temperature at the inlet to the heat exchanger (utility water), T_{zw} [°C],
- water temperature at the outlet from the heat exchanger, T_{pw} [°C],
- exhaust gas temperature, T_{spal} [°C],
- carbon monoxide *CO* [ppm]
- oxygen, O_2 [%].

3 Methodology

In [9], it was observed that boilers operating on actual premises, throughout the year, work in the 10 to 50 % range of their rated power output. On this basis, tests were performed for thermal loads of 30% of the rated power, i.e. 5 kW. Additionally, the exhaust gas was analyzed for the level of carbon monoxide (CO) and oxygen (O_2).

In order to develop the method of identification of a wrong use of the heating equipment the investigations were divided into two stages. In the first one, the boiler was tested according to the PN-EN 303-5 standard [4] using the manufacturer-recommended fuel. The fuel used in the tests was pea coal whose specifications have been presented in table 1.

Table. 1. Specifications of the pea coal used in the investigations

Heating value	21 - 24 MJ/kg
Heat of combustion	25 - 30 MJ/kg
Granulation	5 - 25 mm
Oversize	1 - 10 %
Undersize	0 - 20 %
Sintering ability	7 - 18 %
Humidity	7 - 10 %
Ash	0,5 - 1,0 %
Total sulfur	1 - 10 %

In the second stage of the research, an experiment simulating a wrong use of the boiler was performed under actual conditions of operation. To this end, modifications were made in the design of the boiler to allow using waste material as fuel. The deflector was removed, which made space for the rack. In order to obtain the set power and ensure stable boiler operation the manufacturer-recommended fuel was used as in the first stage of the research.

Then, the boiler was fed with the prepared batch of waste material. Table 2 presents the classification and unit masses of the used waste.

Tab. 2. Classification of the prepared waste

Number of batch	Material	Type of waste	Mass [g/batch]
1	Plastics	Plastic bottle	50
2	Fabric	Footwear	375
3	Analysis waste	Mixture	300
4	Analysis waste	Mixture	600

In order to perform a detailed analysis and confirm the wrong use of the heating equipment the author prepared ‘analysis waste’. The waste was a combination of plastics, fabric, swarf and waste paper. From the prepared waste, the material for analysis was taken for examination under standards applied in coal testing. Table 3 presents the results of the examination.

Tab. 3. Results of the examination of the analyzed waste

Analytical moisture	1,66 %
Volatile parts	77,63 %
Ash	17,59 %
Heat of combustion	20 MJ/kg

4 Results and discussion

Figure 5 presents the curves of the temperature measurement of the exhaust and water at the inlet and outlet from the heat exchanger at approx. 30% rated power. The measurement time was 4000 s (1.11 hrs.). The average power output of the boiler was 5.26 kW. The average temperatures of water at the inlet and outlet from the heat exchanger were 15.1 °C and 59.1 °C respectively. The temperature of the exhaust gas oscillated around 140 °C and 230 °C. The average temperature of the exhaust gas was 178 °C.

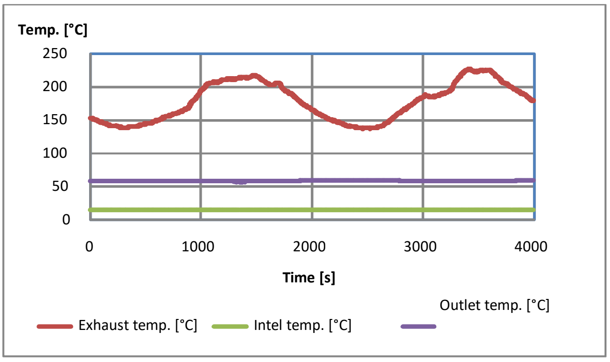

Fig. 5. The measurement of the temperature of the exhaust and water at the inlet and outlet of the heat exchanger at approx. 30% rated power

Figure 6 present the curves of the carbon monoxide CO and oxygen O_2 levels in the exhaust at approx. 30% the rated power. The measurement time was 4000 s (1.11 hrs.). The carbon monoxide CO level oscillated around 330 ÷ 840 ppm. The average value of carbon monoxide CO was 520 ppm. The level of oxygen oscillated around 13.5 ÷ 17%. Its average value was 15.8%.

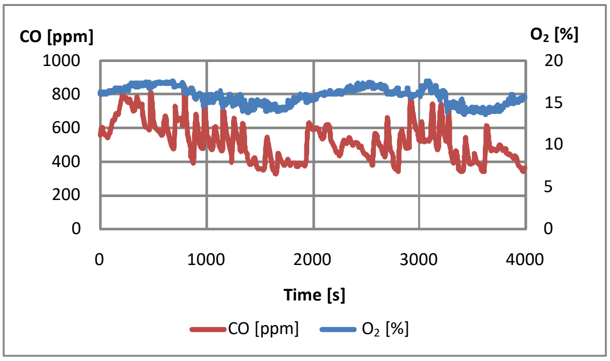

Fig. 6. The level of carbon monoxide CO and oxygen O_2 in the exhaust at approx. 30% rated power

Figures 7 to 11 present the curves of the carbon monoxide CO and oxygen O_2 levels in the exhaust gas at approx. 30% rated power. Figure 7 presents the curve showing the change of the carbon monoxide CO and oxygen O_2 content in the exhaust gas following the opening of the cleaning hatch. The measurement time was 720 s (0.2 hrs.). The hatch was opened for 10 s in the 300th second of the measurement. The carbon monoxide CO level oscillated around 630 ÷ 770 ppm. After this period, the carbon monoxide CO level dropped to 285 ppm and returned to the previous level. The oxygen O_2 level in the exhaust gas oscillated around 14.9 ÷ 16.6%. Upon opening of the cleaning hatch, a sudden increase in the oxygen O_2 level to 20 % was observed and then, when the hatch was closed, the value returned to the level of 14.9 ÷ 16.6%.

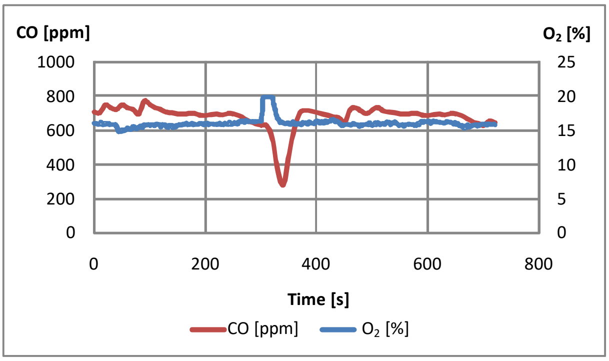

Fig. 7. The level of carbon monoxide CO and oxygen O_2 in the exhaust upon opening of the cleaning hatch at approx. 30 % rate power

Figure 8 presents the curves of the change of the carbon monoxide CO and oxygen O_2 level in the exhaust gas following the introduction of the first portion of waste (a 50g plastic bottle) into the hearth. The measurement time was 660 s (0.18 hrs.). The waste was introduced in the 300th second of the measurement. The level of carbon monoxide CO oscillated around 500 ÷ 865 ppm and the level of oxygen O_2 in the exhaust was in the range from 14.5 ÷ 16.5%. Upon the introduction of the first portion of waste into the hearth the value of oxygen O_2 in the exhaust gas increased drastically to 19.3%, and then dropped to 7.5 %. An increase in the value of carbon monoxide CO to the level of 560 ppm was observed. As the waste incinerated, the levels of oxygen O_2 and carbon monoxide CO returned to their previous values.

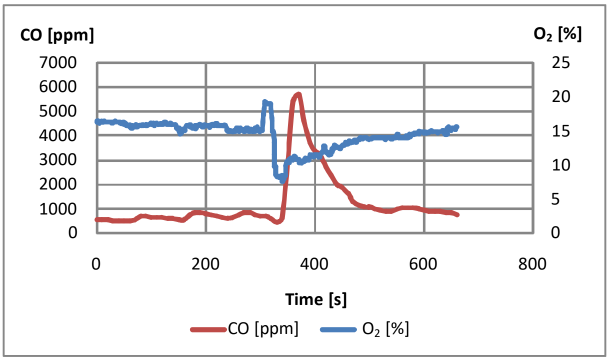

Fig. 8. Carbon monoxide CO and oxygen O_2 levels in the exhaust gas upon introduction of the first portion of waste at approx. 30% rated power

Figure 9 presents the curve indicating the response of the level of carbon monoxide CO and oxygen O_2 to the introduction of the second portion of waste (old footwear) of the weight of 375 g. The measurement time was 1900 s (0.53 hrs.). The waste was introduced in the 300th second of the measurement. The level of carbon monoxide CO oscillated around 560 ÷ 890 ppm and the oxygen O_2 level in the exhaust was in the range from 13.5 ÷ 15%. The introduction of the second portion of waste resulted in a drastic increase in the level of oxygen O_2 to 19.7% and then a gradual drop to 0%. One could observe a gradual increase in the level of carbon monoxide CO to 12000 ppm. As the waste incinerated, the levels of oxygen O_2 and carbon monoxide CO gradually returned to their previous values.

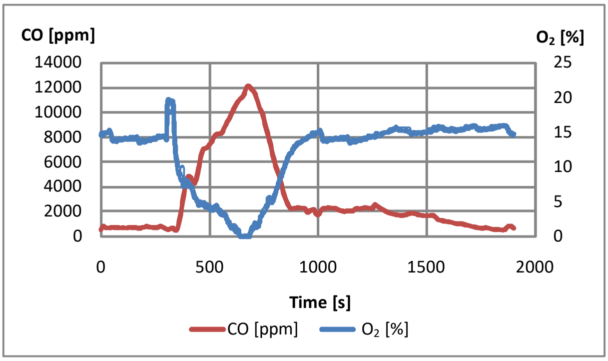

Fig. 9. Carbon monoxide CO and oxygen O_2 levels in the exhaust gas upon introduction of the second portion of waste at approx. 30% rated power

Figure 10 presents the curve indicating the response of the level of carbon monoxide CO and oxygen O_2 to the introduction of the third portion of waste of the weight of 300 g. The measurement time was 1630 s (0.45 hrs.). The waste was introduced in the 300th second of the measurement. The level of carbon monoxide CO oscillated around 610 ÷ 1060 ppm and the oxygen O_2 level in the exhaust was in the range from 12.5 ÷ 15.4%. The introduction of the third portion of waste resulted in a drastic increase in the level of oxygen O_2 to 18.5% and then a drastic drop to a value close to 0% occurred, which continued for approx. 100s. A drastic increase in the content of carbon monoxide CO to the level of 22000 ppm was observed. As the waste incinerated, the levels of oxygen O_2 and carbon monoxide CO gradually returned to their previous values.

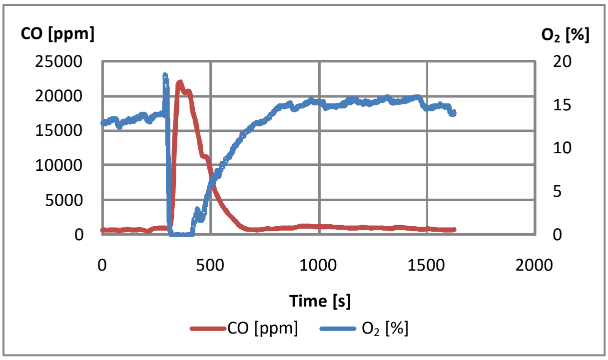

Fig. 10. Carbon monoxide CO and oxygen O_2 levels in the exhaust gas upon introduction of the third portion of waste at approx. 30% rated power

Figure 11 presents the curve indicating the response of the level of carbon monoxide CO and oxygen O_2 to the introduction of the fourth portion of waste of the weight of 600 g. The measurement time was 2260 s (0.63 hrs.). The waste was introduced in the 300th second of the measurement. The level of carbon monoxide CO oscillated around 630 ÷ 810 ppm and the oxygen O_2 level in the exhaust was in the range from 14 ÷ 15,2 %. The introduction of the third portion of waste resulted in a drastic increase in the level of oxygen to 19.9 % and then a drastic drop to a value approximating 0% occurred, which continued for approx. 400s. An increase in the content of carbon monoxide CO to the level of 16800 ppm was ob served. As the waste incinerated, the levels of oxygen O_2 and carbon monoxide CO gradually returned to their previous values.

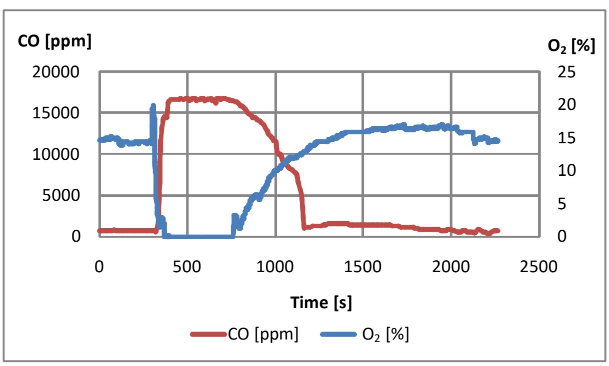

Fig. 11. Carbon monoxide CO and oxygen O_2 level in the exhaust gas upon introduction of the fourth portion of waste at approx. 30% rated power

5 Conclusions

At the first stage of the investigations, the boiler operation was analyzed according to the PN-EN 303-5 standard [4] using the manufacturer-recommended fuel. At this stage, it was confirmed that all conditions for the proper use of the boiler had been satisfied. Table 4 presents the average values of the measurements obtained during the tests.

Tab. 4. Values of the boiler measurements obtained during the tests

Boiler power [kW]	Exhaust temp. [°C]	CO at 10% O_2 [ppm]	O_2 [%]	Efficiency [%]
5,09	178,38	1100	15,8	76

The obtained results correspond to the specifications provided by the manufacturer. The boiler has been certified as 'Environment Friendly Equipment' confirming that it meets the standards of environment protection set forth in the Technical Criteria KT/OS 01-2005. The certificate has been issued by the Institute of Power Engineering.

At the second stage of the investigations, an experiment was performed simulating a wrong boiler use. During the tests, the level of oxygen O_2 in the exhaust gas was monitored. In the beginning, the response to the opening of the cleaning hatch was analyzed (Fig. 7). As a result of the performed trials, it was observed that even a small interference of the user, such as the opening of the hatch, could be detected based on the oxygen O_2 level in the exhaust gas. One can observe its sudden increase to the level of approx. 19 %. A similar relation was observed further during the research. The research consisted in introducing different types of waste material into the hearth (Fig. 7-11). The routine was as follows: a sudden increase in the oxygen level upon opening of the cleaning hatch to introduce the waste material, a drop in the value of oxygen to a level close to zero. This relation was observed for all types of waste material, even small 50g plastic bottles. The time of the oxygen level staying close to zero depended on the weight of the waste material and the power, at which the boiler operated.

The presented results constitute grounds for the development of the method of identification of a wrong use of heating equipment under actual conditions of operation. Another stage of the research will be the observation of the response of the exhaust gas temperature to the use of waste material as fuel. Additionally, the experiment will be extended by tests performed on heating devices of different designs.

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