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Combustion of wood pellets in a low-power multi-fuel automatically stoked heating boiler

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Abstract This paper presents a test stand equipped, among others, with two boilers intended for the combustion of solid fuels. The first is a single-fuel boiler designed to burn wood pellets only. The second is a multi-fuel boiler intended for the combustion of mainly hard coal (basic fuel) with the grain size of 0.005–0.025 m. Wood pellets can also be fired in this boiler, which in such a case are treated as a substitute fuel. There is a developed and verified algorithm for the control of the multi-fuel boiler operation in a wide range of loads for the basic fuel. However, for the substitute fuel (wood pellets) there are no documented and confirmed results of such testing. The paper presents selected results of testing performed during the combustion of wood pellets in a multi-fuel automatically stoked boiler. Several measuring series were carried out, for which optimal operating conditions were indicated. These conditions may serve as the basis for the development of the boiler operation control algorithm. A detailed analysis was carried out of the flue gas temperatures obtained at the outlet of the boiler combustion chamber and of the contents of carbon monoxide and oxygen in the boiler flue gases.

Keywords: Multi-fuel heating boiler; Wood pellets; Substitute fuel; Thermal tests; Boiler optimal operating points

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Nomenclature

P	–	pause, s
t	–	temperature, °C
T	–	operation time, s
$\dot{V}$	–	volume flow rate, %, m^3/s

1 Introduction

For a few decades both Poland and Europe have shown an increased interest in renewable energy sources (RES). This is due to the general increase in the awareness of the Old Continent's public of the depletion of fossil fuels. In addition, the negative impact of the pollution of the atmosphere by products of the combustion of fossil fuels on the natural environment is becoming more and more visible. This especially concerns the emissions of dusts and carbon dioxide, which is perceived as the gas responsible for the greenhouse effect. The above-mentioned problems also affect households, where the production of energy needed for heating and hot water preparation is very often based on firing fossil fuels. Efforts are therefore made in Poland to achieve a reduction in the emissions of pollutants into the atmosphere by implementing, among others, the act on renewable energy sources [1], the regulation on the requirements for solid fuel boilers [2] and the standard requirements set out in [3]. In order to meet these requirements, an increased interest should be expected in biomass combustion in households. Moreover, legal regulations in the form of anti-smog resolutions are gradually being introduced in Poland. An essential strategic instrument adopted by the Polish government is the document called "Poland's Energy Policy until 2040" [4]. It sets out the development directions for the Polish fuel and energy sector. One of the key elements of the document is that in 2030 renewable energy sources will have at least a 23% share in the gross final consumption of energy. It is expected that biomass will have the greatest potential for meeting the RES target in heating engineering, but also in cogeneration and in households. In the European arena, the development of RES, also in the form of biomass, is included, among others, in the EU regulation [5] and the European Parliament directive [6]].

The structure of currently used central heating boilers and the ever-increasing requirements for their operation require the usage of modern devices with a higher degree of automation in the field of temperature control, fuel feeding, and combustion process. Manufacturers of single-fuel boilers fired with hard coal and of multi-fuel boilers in Poland are now facing the urgent need to substantially upgrade their products. The modernization of low-power multi-fuel boilers consists mainly in adapting them to the combustion of other fuels, e.g. wood pellets, which makes it necessary to develop a suitable algorithm to control the boiler operation in a wide range of loads using this kind of fuel. Such algorithms for the combustion of the commercial variant of hard coal with the grain size of 0.005–0.025 m have already been developed and are giving satisfactory results. However, there are not enough experiments and verified algorithms for multi-fuel boilers firing pellets as a substitute fuel. Moreover, the literature analysis indicates that the combustion of pellets causes operational problems also in single-fuel boilers, designed for firing this fuel only. One example is the slagging of burners [7]. The problem was addressed in [8], whose authors presented the results of an experiment where agro-biomass pellets were fired with additives to raise the ash melting point. This was meant to avoid slagging that impedes the combustion process. The experiment was carried out in a 20 kW heating boiler with a retort furnace. An analysis of the possibility of co-firing wood pellets with wheat seeds in a modern heating boiler is presented in [9]. The research made it possible to determine the effect of such co-firing on the degree of the environmental impact of the emissions of harmful substances. The authors of [10] present the results of certification testing of a 21 kW automatically stoked boiler adapted for the combustion of biomass in the form of pellets. The literature analysis thus indicates that wood biomass in the form of pellets is becoming an increasingly popular biofuel. This also applies to manufacturers of multi-fuel boilers with automatic fuel feed, who show great interest in the testing results obtained from the combustion of this particular fuel. The expectations of boiler manufacturers in this respect contributed to the construction, in the laboratory of the Department of Energy of the Cracow University of Technology, of a modern test stand equipped with boilers fired with solid fuels. The stand includes a low-power multi-fuel boiler with automatic fuel feed, which is intended for the combustion of mainly hard coal with the grain size of 0.005–0.025 m. The boiler was used to carry out a number of tests and measurements during the combustion of wood pellets used as a substitute fuel. The first results of the testing were presented, among others, in [11].

The issues discussed in the present paper can be taken into account in a thermo-ecological approach when analyzing the results of energy efficiency improvements [12].

2 Brief description of the test stand

The test stand in the Department of Energy laboratory of the Cracow University of Technology (Fig. 1) is a stationary structure enabling thermal testing of automatically stoked central heating boilers and of solar collectors. The test stand enables continuous measurements of temperature, volume flows of working fluids and flue gases. The measured quantities are recorded online by a data acquisition system. Additionally, the test stand is equipped with portable analysers for continuous measurement of the chemical composition of flue gases. The data collected by the analysers are archived as well.

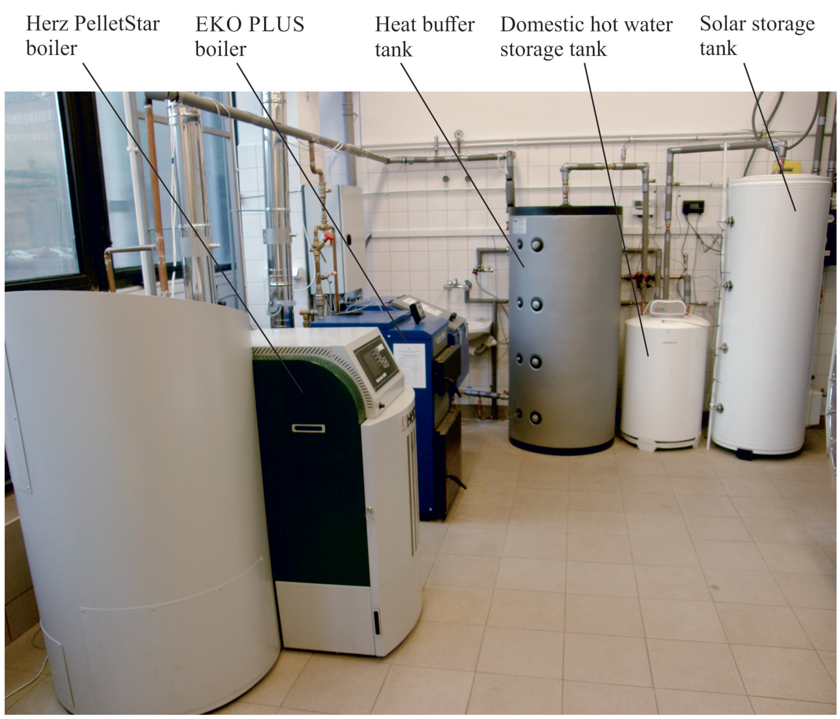

Figure 1: System including technological tanks and solid-fuel boilers.

The test stand is equipped with two low-power heating boilers, two flat liquid solar collectors, three technological tanks, installations of the working fluids, a flue gas discharge installation and a data acquisition system (Fig. 2). The technological tanks include the heat buffer, the hot water storage tank and the solar storage tank. The heat buffer is intended to store the thermal energy carried by the heating fluid. It has connector pipes located at different levels to feed and carry out the heating fluid with a different temperature. The heat buffer also has a spiral immersion heat exchanger, and its capacity totals 0.5 m^3. The hot water storage tank and the solar storage tank capacities are 0.3 m^3 and 0.12 m^3, respectively. All the tanks are thermally insulated. Two commercially available solid-fuel boilers, the PelletStar BioControl 10 [13] and the Eko Plus 10 [14], are connected to the test stand. The flue gases are analysed using two portable analysers: GreenLine 6000 and GreenLine 8000.

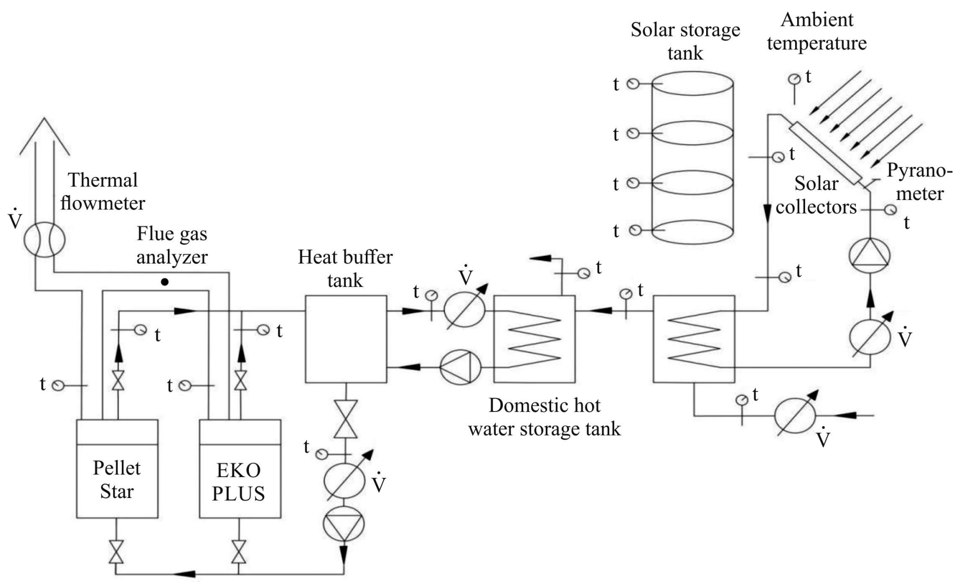

Figure 2: Diagram of the test stand: t – temperature measurement, $\dot{V}$ – volume flow measurement.

The hot water storage tanks and the heat buffer are connected to the boilers through a closed water system. The system is made of copper pipes. The water system is equipped with elements of hydraulic regulation, temperature regulation (three-way valves), cut-off and drain valves, filters, circulation pumps and a control and measurement apparatus. The apparatus includes direct-reading meters and those integrated into the data acquisition system.

The flue gases are carried away through single-walled steel pipes of a chimney system with the diameter of 0.13 m. The boiler flues are fitted with sensors for the measurement of the flue gas temperature and stub pipes for the connection of the flue gas analyser. A thermal flowmeter is installed on the common flue pipe. The temperature sensors and the thermal flowmeter are connected to the data acquisition system.

2.1 Boiler characteristics

As already mentioned, the test stand includes two low-power boilers fired with solid fuels (Fig. 1). They are automatically stoked devices. The PelletStar 10 is a steel boiler with the nominal power of 10 kW and operating range of 3.4–13.5 kW. The boiler nominal efficiency is 91.5%, the maximum operating temperature is 95°C and the maximum operating pressure is 3 bar. It is a single-fuel stoker-fired boiler designed exclusively for the combustion of wood pellets classified according to standard specification. Its structure takes account of individual physical and energy-related features of this fuel, as well as the specificity of the combustion process. This boiler is the "reference boiler" for the analysis and for the setting of operating parameters of the multi-fuel boiler for which wood pellets are a substitute fuel.

The Eko Plus 10 boiler is also a steel boiler, whose basic fuel is hard coal with the grain size of 0.005–0.025 m. The boiler nominal power totals 10 kW and its operating range varies between 3 and 14 kW. The boiler efficiency is 84.8%, the maximum operating temperature is 90°C and the maximum operating pressure is 2 bar. It is a multi-fuel boiler with a retort burner which, as specified by the manufacturer, can be fed with a substitute fuel in the form of wood pellets. For the basic fuel the emissions of pollutants into the atmosphere is known, certified by the 'ecological safety mark' [15]. Moreover, for the basic fuel there is a developed and verified algorithm to control the boiler operation in a wide range of loads. There are no documented and confirmed testing results for the substitute fuel. Although the boiler controller offers the option to select wood pellets as fuel, the algorithm controlling the boiler operation has not in this case been developed based on earlier testing. One effect of this situation is fast combustion of fuel in the entire volume of the retort burner, up to the level of the screw feeder [11], whereas the combustion process should instead be realized on the upper part of the retort, in the air supply area.

This paper presents selected results of testing performed during the combustion of wood pellets in this particular boiler for several levels of the thermal load.

2.2 Quantities measured on the test stand

The stand enables continuous measurements of quantities such as the temperature and volume flow of the working fluid and flue gases – according to the test stand diagram (Fig. 2). Temperature is measured using type T (Cu-CuNi) and type K (NiCr-Ni) thermocouples. The former are sensors with a single sheathed thermocouple with the measuring range of $-40-350$°C. The thermocouples are made in Class 2 according to the EN 60584 standard. The temperature measurement error depends on the measuring range and totals ± 1°C and $\pm 0.0075t$ for the ranges of $-40-133$°C and $133-350$°C, respectively. The K-type device is also a sensor with a single sheathed thermocouple, but its measuring range is from -40°C to 1000°C. This thermocouple is made in Class 1 according to the EN 60584 standard. The temperature measurement error is ± 1.5°C and $\pm 0.0045t$ for the ranges of $-40-375$°C and $375-1000$°C, respectively. The K-type thermocouple is installed at the outlet of the Eko Plus boiler combustion chamber; it is intended to measure the flue gas mean temperature. The working fluid volume flow is measured using turbine flowmeters for liquids of the FVA 915 (Ahlborn product) and HO (Hoffer Flow Controls) series. The volume flow rate of cold water was measured using the HO flowmeter with the measuring range of 4.7–36 l/min and the measuring accuracy of $\pm 0.5\%$. The other measurements of the working fluid volume flows were performed using the FVA 915 flowmeter with the measuring range of 2–40 l/min and the measuring accuracy of $\pm 1\%$. The flue gas volume flow rate was measured using an ST98 thermal mass flowmeter with a high-temperature sensor intended for polluted gas measurements with temperature compensation. This flowmeter is installed on the flue gas duct with the outer diameter of 0.13 m. A straight section with the required length of 2.6 m was maintained upstream the installed flowmeter. The measuring range is from 16 Nm^3/h to 172 Nm^3/h with the measuring accuracy of 1.11% of the indicator reading $+0.5\%$ of the measuring range.

Additionally, the test stand is equipped with GreenLine 6000 and GreenLine 8000 flue gas analysers [16]. They are portable analysers intended for continuous measurement of the flue gas chemical composition and fitted with a state-of-the-art system for data acquisition and transmission of the measured values. The analysers make it possible to measure such flue gas constituents as CO, CO_2, NO, NO_2, SO_2, H_2S, NO_x, and C_xH_y. In addition, the flue gas temperature, pressure, the chimney draught and the flow velocity are measured and the combustion efficiency is calculated.

2.3 Data acquisition system

The values of all the measured quantities are recorded online and archived by a data acquisition system (Fig. 3). The data acquisition system co-operates with a system visualizing the measured quantities and makes it possible to observe them online on a display monitor.

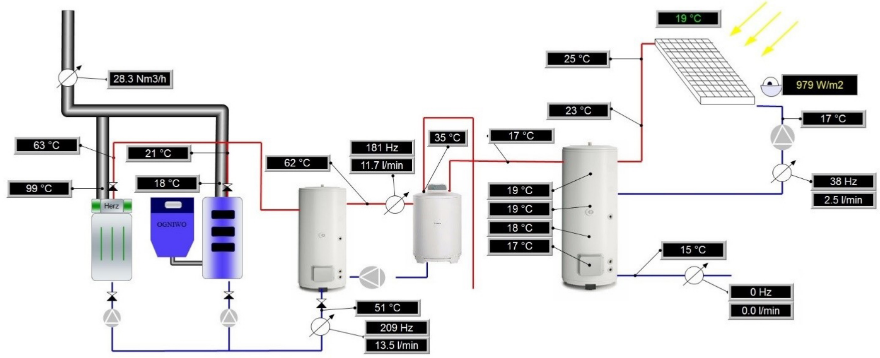

Figure 3: Visualisation of the data acquisition system.

3 Measuring procedure

The measurement procedure described below applies to tests carried out during the operation of the Eko Plus multi-fuel boiler only, when wood pellets were fired as a substitute fuel.

The quantities measured and archived by the data acquisition system are shown in Figs. 2 and 3. The cycles of the screw feeder operation (operation time, so-called *tact* – T) and shutdown (so-called *pause* – P) are also identified. Based on that, it is possible to calculate basic input and output data characterizing the combustion process and the tested boiler, such as the chemical energy flux supplied to the combustion chamber with fuel, the boiler heating power and the boiler efficiency. The portable flue gas analysers installed on the test stand make it possible to determine the level of the emissions of pollutants to the atmosphere in individual cycles of the analysed boiler operation. The Eko Plus boiler controller enables operation in the automatic and in the manual mode. In the latter case, the time of operation (T) and the time of the pause (P) can be set individually. As it was difficult to establish the fuel mass flow to the combustion chamber in the automatic mode of the boiler operation (the operation and pause cycles varying over time), the tests were carried out in the manual-control mode. In order to fully identify the mass flow of fuel fed into the combustion chamber, the bulk density of wood pellets and the volume output of the screw feeder were determined for continuous operation. The fired fuel bulk density was 674 kg/m^3. The screw feeder volume output for continuous operation totalled 0.0124 m^3/h. Knowing, the bulk density of the pellets, the screw feeder volume output and the times of the feeder operation (T), the time-averaged mass flow of fuel fed into the combustion chamber was calculated in each measuring series.

Knowing the input parameters, i.e. the fuel and air flows to the combustion chamber, and the output parameters of the flue gases and the heating fluid, the boiler can be parametrized in terms of energy. In the manual-control mode, the output parameters were scanned during the boiler operation at different values of the air and fuel flows supplied to the combustion chamber. The values close to those identified during the boiler operation in the automatic mode were adopted as the initial values of the flows, selecting pellets as the (substitute) fuel. The volume flow of air supplied into the combustion chamber was set by selecting a given percentage of the fan output on the boiler controller. At the same time, the flue gas volume flow was measured and the volume flow of fresh combustion air supplied to the combustion chamber was checked. Based on the set values of the forced-draught fan output and on the measured values of the flue gas volume flow (for different T-to-P ratios), curves were developed illustrating changes in the flue gas temperature, carbon monoxide emissions and oxygen content during the boiler operation depending on the fan percentage output (Figs. 4–6). The scanning of the boiler operation at different conditions of the fuel and the combustion air supply was carried out in measuring series. In each of the series the (averaged) volume flow of fuel was kept constant and the volume flow of combustion air was varied. Four main measuring series were performed along with reruns.

During the testing on the test stand the measuring series presented in Table 1 were adopted. The results of the calculations related to momentary

Table 1: Measuring series parameters.

T/P	Operation time, s	Pause time, s
20/20	20	20
15/20	15	20
10/20	10	20
5/20	5	20

values of the boiler power and efficiency for the adopted T/P ratios are presented in [11].

4 Selected measurement results and their analysis

Selected results of the measurements performed in the four main measuring series are shown in Figs. 4–6. In the diagram presenting the measured values of the flue gas temperature at the combustion chamber outlet (Fig. 4), a temperature maximum ($t1$, $t2$, $t3$, $t4$) can be observed for each T/P measuring series. The values rise with an increase in the fuel mass flow to the combustion chamber (5/20, 10/20, 15/20, 20/20) and are shifted to the right in the diagrams with an increase in the fan output ($\dot{V}1$, $\dot{V}2$, $\dot{V}3$, $\dot{V}4$). In individual series, the values of the flue gas maximum temperature fall on the line connecting the maximum temperatures of flue gases at the combustion chamber outlet, the thick line shown in Fig. 4. The fan percentage output ($\dot{V}1, \dot{V}2$, $\dot{V}3$, $\dot{V}4$) can be assigned to each maximum temperature in a given T/P measuring series.

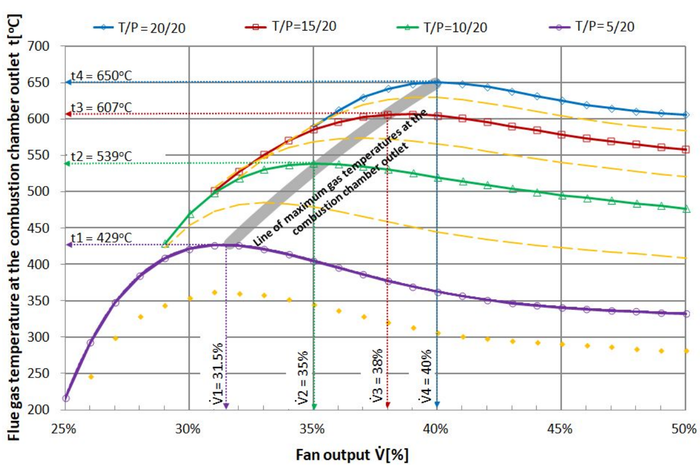

Figure 4: Flue gas temperature measured at the combustion chamber outlet (dashed and dotted lines: example values between the measuring points).

The values between the maximum measuring points ('line of maximum gas temperatures at the combustion chamber outlet') can be interpolated using

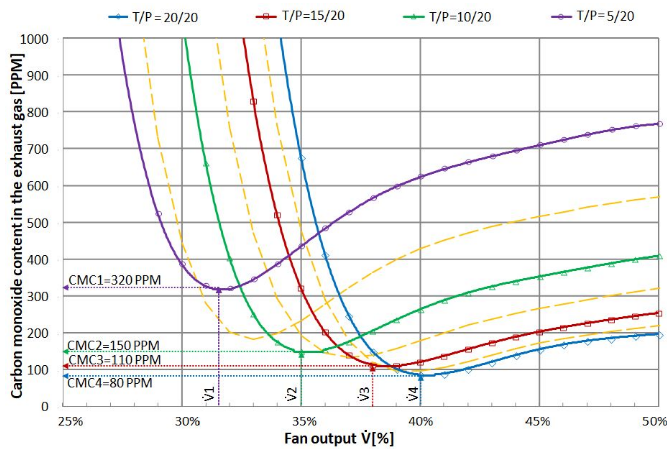

Figure 5: Carbon monoxide content in flue gases (dashed lines: example values between the measuring points).

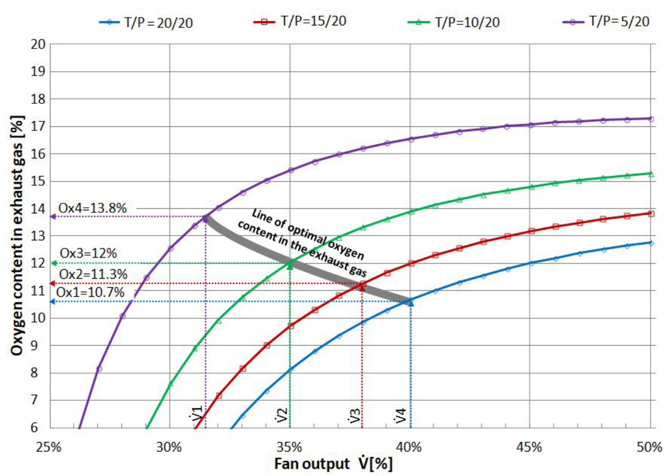

Figure 6: Measured content of oxygen in flue gases.

the following relation:

$$t_{\max} = -1.05 \times 10^4 \left(\frac{\dot{V}}{100}\right)^2 + 1.01 \times 10^4 \frac{\dot{V}}{100} - 1.71 \times 10^3, \qquad (1)$$

where $\dot{V}$ is the volume flow rate of air (fan output) in %.

The flue gas temperature was measured in parallel with the measurements of the contents of carbon oxide and oxygen in flue gases. The measurement results were used to make relevant diagrams (Figs 5–6). The points of the occurrence of the flue gas maximum temperatures at the combustion chamber outlet (Fig. 4) correspond to the points of the minimum carbon monoxide content (CMC) in flue gases (CMC1, CMC2, CMC3, and CMC4 in Fig. 5). This is due to the best conditions for the combustion process to occur in the combustion chamber in these points. The highest temperature of flue gases in a given measuring series makes it possible to ensure maximal combustion of carbon monoxide (CO) to carbon dioxide (CO_2).

For each measuring series, a reduction in the fan output below maximum values involves a fast drop in the flue gas temperature in the combustion chamber (Fig. 4). This is due to incomplete combustion of carbon contained in the fuel, which causes an abrupt rise in the carbon monoxide content in flue gases above the minimum values CMC1, CMC2, CMC3, and CMC4 for consecutive measuring series (Fig. 5). A smaller amount of air fed into the combustion chamber means less oxygen, which in turn means that carbon, being the fuel less reactive constituent, is not burnt completely. A further reduction in the amount of combustion air resulted in soot formation. Imperfect and incomplete combustion also means less heat released in the combustion chamber. A smaller amount of supplied air does not stop the endothermic process of gasification, but it impedes the exothermic process of combustion. Both these mechanisms naturally cause a reduction in the flue gas temperature in the combustion chamber.

If the volume flow of air supplied to the combustion chamber increases above values $\dot{V}1$, $\dot{V}2$, $\dot{V}3$ and $\dot{V}4$, there is a gentle asymptotic decrease in the flue gas temperature at the combustion chamber outlet, and thus also in the chamber itself (Fig. 4). This is caused by the introduction of unnecessary ballast air, which heats up by absorbing heat from flue gases with no participation in the combustion process. A bigger volume flow of the mixture of flue gases and additional air means a higher velocity of the moving gases and thus their shorter time of residence in the combustion chamber. This is accompanied by a rise in the carbon monoxide content in flue gases (Fig. 5) due to the shortened time of the flue gas exposure to high temperature, and the lower temperature of the combustion chamber.

The operating points of the boiler at the maximum temperature in the combustion chamber ($t1$, $t2$, $t3$, and $t4$ in Fig. 4), which correspond to the lowest concentrations of carbon monoxide in flue gases (CMC1, CMC2, CMC3, and CMC4 in Fig. 5), are the optimal points of the boiler operation.

Based on the determined line of the flue gas maximum temperatures (Fig. 4), the boiler operation control algorithm can be created. For any other value of the fuel mass flow to the combustion chamber, between the analysed minimum ($T/P = 5/20$) and maximum ($T/P = 20/20$) ranges, it is possible to determine the fan optimal output, which will correspond to the highest temperature in the combustion chamber and thus – the minimum level of emissions of carbon monoxide to the atmosphere. To derive and formulate appropriate relations in the boiler operation control algorithm (e.g. the relation describing the fan output as a function of the fuel volume flow) is a simple matter. The momentary mass or volume flow of the fuel fed into the combustion chamber is a function of the boiler momentary load, whereas the volume flow of combustion air depends on the line of the maximum temperatures in the combustion chamber. Using the percentage output of the fan is a convenient solution in terms of a practical realization of the output by means of an inverter. If absolute volume flow rates of air, expressed in m^3/h, are used, a problem arises with the flow reliable measurement.

The described tests were carried out for a typical fuel that meets the energy requirements of the fuel standard. To avoid operational problems due to a change in the fuel quality, the manufacturer should additionally equip the boiler with a temperature sensor placed in the combustion chamber (or at the chamber outlet) to enable dynamic corrections in the control algorithm. Such a sensor is not included in the investigated boiler standard equipment. It is installed, however, in the PelletStar boiler. Oxygen concentrations in flue gases for individual points of maximum values of the flue gas temperature and minimum contents of carbon monoxide are different for each measuring series (Fig. 6). The oxygen concentration in flue gases for the analysed operating points of the boiler is the highest for $T/P = 5/20$ ($Ox4$) and the lowest for $T/P = 20/20$ ($Ox1$). The oxygen concentrations in the boiler optimal working points ($Ox1$, $Ox2$, $Ox3$, and $Ox4$) constitute the line of the optimal content of oxygen in flue gases for the series. The line can be the line of the fan output control (alternative regulation path) to achieve the boiler optimal operating point for a given load. The values between the measuring points (thick line of optimal oxygen content in the exhaust gas in Fig. 6) can in this case be interpolated using the following relation:

$$Ox_{\max} = 2.438 \times 10^2 \left(\frac{\dot{V}}{100}\right)^2 - 2.097 \times 10^2 \frac{\dot{V}}{100} + 55.63, \tag{2}$$

where $\dot{V}$ is the volume flow rate of air (fan output) in %.

If the boiler momentary load is related to the fuel feeder output, the fan percentage output can be read on the line of the optimal content of oxygen in flue gases. To ensure the boiler optimal operation if the fuel quality deviates from the quality of the reference fuel for which the tests were carried out, the boiler should be equipped with a lambda probe, installed in the flue gas duct. The lambda probe will make it possible to correct the control algorithm for fuels with a slightly different bulk density, a different calorific value or changeable hydraulic conditions of the flue gas flow, such as an excessive chimney draught for example.

Moreover, for real conditions of the boiler operation, the flue gas temperature at the combustion chamber outlet was calculated using the CKTI method [17]. This method was developed mainly for power boilers with pulverized fuel furnaces. According to literature analysis, the method can also be used for other boilers, e.g. for grate boilers [18]. Assuming that the flue gas temperature throughout the furnace chamber is constant, the method was used in the present work for a boiler with a retort burner.

Table 2 presents a comparison between the calculated and measured values of the temperature, lying on the line of maximum values. The obtained convergence of the results proves the correctness of the assumptions adopted for the calculation model. The model can be used to calculate the flue gas temperature at the outlet of the combustion chamber between the analysed measuring points. Based on the testing results, the area of the boiler operation can be narrowed down to the range with a high thermal efficiency and a low level of carbon monoxide emissions.

Table 2: Comparison of measured and calculated maximum values of the flue gas temperature at the boiler combustion chamber outlet.

T/P	Measured value, °C	Calculated value, °C
20/20	650	655
15/20	607	603
10/20	536	540
5/20	431	428

5 Conclusions

Thermal tests were carried out of a low-power multi-fuel heating boiler with automatic fuel feed when wood pellets were fired in it as a substitute fuel. The obtained results were used to make diagrams illustrating changes in the flue gas temperature at the combustion chamber outlet and in the contents of carbon monoxide and oxygen in flue gases at the boiler outlet. The tests were performed at different values of the fuel feeder output and the fan percentage output.

A temperature maximum can be observed for each series in the diagrams of the flue gas temperature at the outlet of the combustion chamber plotted for different measuring series (with different times of fuel feeding and the same time of the pause). These maxima for the four measuring series under analysis fall along a line referred to as the line of the maximum temperature of flue gases at the combustion chamber outlet. An appropriate mathematical notation of this line enables interpolation of values between measuring points.

Analysing the diagrams illustrating the content of carbon monoxide in flue gases for the adopted measuring series, the occurrence of a minimum can be observed in each case. It is found that the minima occur for the fan output corresponding to the maximum values of the flue gas temperature at the combustion chamber outlet.

Considering the observed relationships between the parallel occurrence of maximum values of the flue gas temperature at the combustion chamber outlet and minimum contents of carbon monoxide in flue gases, a proposal was made to introduce a relation into the boiler operation control algorithm based on the maximum temperature of flue gases at the outlet of the combustion chamber. This will make it possible for the boiler to operate at optimal points in terms of energy and carbon monoxide emissions into the atmosphere.

It was also observed that for the boiler optimal operating points that were found, the content of oxygen in flue gases varied. The values of the content fall along a line referred to as the line of the optimal content of oxygen in flue gases. An appropriate mathematical notation of this line will enable interpolation of the optimal values of the oxygen content in flue gases between measuring points. The oxygen content line determined in this manner can become an alternative path of the boiler regulation. To ensure appropriate operation of the boiler, at a varying bulk density and calorific value of pellets, a proposal was made to install a temperature sensor at the boiler combustion chamber outlet and a lambda probe in the boiler flue gas duct to correct the developed control algorithm.

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References

[1] Announcement of the Sejm Speaker of the Republic of Poland on the promulgation of a consolidated text of the Act on renewable energy sources. Journal of Laws – Republic of Poland (Dziennik Ustaw Rzeczypospolitej Polskiej) 2021, Item 610 (in Polish).

[2] Regulation of the Minister of Development and Finance on the requirements for solid-fuel boilers. Journal of Laws – Republic of Poland (Dziennik Ustaw Rzeczypospolitej Polskiej) 2017, Item 1690 (in Polish).

[3] EN 303-5:2021: Heating boilers – Part 5: Heating boilers for solid fuels, manually and automatically stoked, nominal heat output of up to 500 kW – Terminology, requirements, testing and marking.

[4] *Poland's Energy Policy until 2040*. Ministry of Climate and the Environment, Appendix to Resolution 22/2021 of the Council of Ministers, 2021 (in Polish).

[5] Commission Regulation (EU) 2019/2146 amending Regulation (EC) 1099/2008 of the European Parliament and of the Council on energy statistics, as regards the implementation of updates for the annual, monthly and short-term monthly energy statistics. OJ L 325, 16.12.2019.

[6] Directive (EU) 2018/2001 of the European Parliament and of the Council on the promotion of the use of energy from renewable sources. OJ L 328, 21.12.2018.

[7] Zima W., Ojczyk G.: *Current status and prospects for solid multi-fuel boilers of low power*. Rynek Energii **5**(2013), 108, 50–56 (in Polish).

[8] Juszczak M., Pałaszyńska K., Rolirad K., Janicki M., Szczechowiak E.: *Attempt to use additives increasing ash melting point while firing agricultural biomass pellets in order to avoid slag production in the furnace*. Ciepłownictwo, Ogrzewnictwo, Wentylacja **48**(2017), 8, 320–326 (in Polish).

[9] Ciupek B., Urbaniak R., Judt W.: *Experimental research of changes in co, nox and pm concentrations in flue gases during combustion of wood pellets with wheat seeds*. Ciepłownictwo, Ogrzewnictwo, Wentylacja **50**(2019), 2, 56–61.

[10] Orłowska A., Sroka K.: *Changes in legal regulations concerning supplying households with heat*. Rynek Energii **140**(2019), 1, 38–47.

[11] Zima W., Ojczyk G.: *Analysis of combustion of wood pellets as a substitute fuel in a low-power boiler*. Arch. Combust. **35**(2015), 2, 117–130.

[12] Ziebik A., Stanek W.: *Energy effciency – selected thermo-ecological problems*. Arch. Thermodyn. **41**(2020), 2, 277–299.

[13] https://www.herz-energie.at/pl/ (accessed 6 Sept. 2021).

[14] http://www.ogniwobiecz.com.pl/ (accessed 12 Sept. 2021).

[15] Ecological Safety Mark: Certificate 1035. Inst. Chem. Process. Coal, Zabrze 2009 (in Polish).

[16] https://www.keison.co.uk/ (accessed 17 Aug. 2021).

[17] Kuznetsov N.V., Mitor V.V., Dubovsky I.E., Karasina E.S. (Eds.): *Thermal Calculation of Steam Boilers. Normative Method* (2nd Edn.). Energia, Moscow 1973 (in Russian).

[18] Rutkowski Ł., Szczygieł I.: *Calculation of the furnace exit gas temperature of stoker fired boilers*. Arch. Thermodyn. **42**(2021), 3, 3–24.