The efficiency of bark and wood fuel utilization in the hot water boilers

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Abstract. The commissioning of a hot water boiler house at SJSC “Sawmill 25” was another major step in increasing of efficiency of the integrated use of wood raw in the enterprise. It required efficiency assessment of burning bark and wood fuel in the combustion chambers of PR 8000 boilers. For this purpose, the comprehensive energy audit of boiler house equipment was carried out, the biofuel mixture as fired and the residues of combustion were analyzed. The moister content of bark and wood fuel was 50.83 – 54.82 %. The proportion of bark in the fuel varied in the range from 55 to 77 %. As a result of the energy audit, the components of boilers heat balance were calculated. In this case, combined relative and calorimetric method supplemented with thermal imaging was used to determine external heat loss. Gaseous and particulate emissions were determined with electrochemical and weight methods. Distribution of combustibles in fly ash fractions was analyzed. The overall separation efficiency of gas cleaning plants was determined. Gas-entrained soot particles were studied with an electronic scanning microscope. Based on the analysis, recommendations were elaborated to improve the energy-ecological performance of the tested boiler house and to reduce the emission of particulate matter. Measures for partial or complete removal of restrictions on the furnace draft when burning bark and wood fuel with a relative moist content of more than 55% were proposed. The energy audit showed that the design characteristics of the main and auxiliary equipment of PR-8000 boiler provide sufficiently high energy-ecological performance if the grates surfaces are used effectively and the vacuum in the combustion chambers is close to the optimum values.

1. Introduction

The level of technically available renewable energy resources (RER) in the Russian Federation (RF) is equivalent to no less than 4.6 billion tons of reference fuel. However, without governmental incentive it is economically feasible to use only a part of available RER at the current conjuncture and the level of technological development in the world energy markets. Currently, the total installed capacitance of RER-based power generators and power station plants in the RF is less than 2200 MW.

Increasing of RER-based heat and power industry efficiency is a prerequisite for the reliable, sustainable and long-term energy supply of economic development in the RF. It promotes the involvement of innovative high technologies and processes into energy area and it is one of the significant activities related to the international obligations of the RF in limiting greenhouse gas emissions [1 - 2].
In 2018, CJSC “Sawmill 25” completed a project to modernize the third section of the sawmill and wood-processing plant based on OJSC “LDK No. 3”. One of the stages of modernization was the construction of a new boiler house to meet the production needs.

The objectives of this paper are the energy and environmental performance research of the hot water boiler house and the development of recommendations for technical and economic improvement of its performance.

2. Experimental methods
While performing work on the energy audit the following tests were carried out: inspection of elements of boilers; calibration of air and gas paths; study of thermal and granulometric characteristics of fuel and focal residues; balance experiments; analysis of technical, economic and environmental performance of boilers.

Balance experiments were carried out in accordance with the requirements for production and operational testing of the third category of complexity which are pre-calibrated sections of air and gas ducts; measurement of air velocity in air ducts; determination of air inleakage into gas path including the ash collector, etc. When carrying out balance experiments we determined the optimal coefficient of excess air at several loads, efficiency and heat losses at nominal and three reduced loads, maximum and minimum loads.

Methods of production and operational testing of the boiler-furnace and auxiliary equipment are: electrochemical method applied to flue gas analyzers, pressure and optical methods for determination of the volume of gas and air flow, ultrasonic fluid flow method, aspiration gas sampling method, thermal, pyrometric and contact methods for determination of the temperatures, combined relative and calorimetric methods supplemented by thermal imaging, weight and chemical methods for determination of the elemental composition of fuel, combustion residues, etc. [3, 4, 6].

Moisture, ash content, volatiles, low calorific value as received were determined in each of the main experiments for the sampled fuel. Experimental data analysis was performed using multiblock program-methodological complex [5].

3. Target of research
The boiler house is equipped with two 8 MW Polytechnik PR-8000 boilers and provides the process heat load and its own needs for hot water with the temperature of up to 110 °C and a pressure of up to 6 bar. The boilers have two-pass fire-tube heat exchangers located horizontally along the longitudinal axis above the combustion chamber. The chamber consists of reciprocating grate with 27 rows of fire-bars. Furnace charging proceeds in the clock mode in dependence on the heat demand of consumers, composition and moisture content of the fuel, the temperature of brickwork, the oxygen content in the flue gases and the state of photobarriers. Under the reciprocating grate three zones are organized by partitions with individual supply of primary air that is supplied by three fans, two of which supply hot air coming from the air heater to the first and second combustion zones. The third fan delivers air heated in the cooling system of the enclosure surface of the furnace in the third zone respectively. Each fan has a variable-frequency drive. Furnace temperature control systems, control air supply, draft and consumption of recycled flue gases are provided to ensure high completeness of combustibles burn-off and failure-free operation of the hot water boiler.

The range of boilers load changes during the tests was limited by the process heat load of the boiler house № 3 of CJSC “Sawmill 25”. The total consumption of bark and wood fuel in the studied load range per boiler was 2.468–4.34 tons per hour.

4. Results and Discussions
During the production and operational testing one boiler was in operation at a time. Theirs heat output varied from 63.0 to 98.4 % of rated load.
In the course of testing a series of experiments for different operating modes of the boilers were carried out. Key results of the balance experiments are presented in Table 1. Unsorted bark and wood fuel were fed into the boilers’ furnaces. The main fraction of the fuel was bark. The bark fraction in the biofuel was 55–77 %. In all experiments, burned bark and wood fuel had a high level of heterogeneity of grain-size distribution (an average coefficient of polydispersity was \( n = 0.794–0.819 \) and a coefficient characterized particle size was \( d = 0.089\cdot10^3–0.151\cdot10^3 \)). Mass fraction of biofuel pieces of 25 mm or larger in size was 63–70 %. Bark and wood fuel moisture content as received over the course of the tests was 50.83–54.82 %; ash content was 1.08–1.12 %; low calorific value was 7290–8175 kJ/kg. These thermal and size distribution characteristics of wood fuel are acceptable for boilers with combustion chambers of this type.

### Table 1. Results of the study of the boiler house of SJSC “Sawmill 25”.

| Value                               | Dimension | Boiler No. 1 | Boiler No. 2 |
|-------------------------------------|-----------|--------------|--------------|
| Heat output                         | MW        | 5.7-7.9      | 5.1-6.1      |
| Furnace air excess                  | -         | 1.29-1.36    | 1.17-1.42    |
| Excess air in flue gas              | -         | 1.39-1.46    | 1.27-1.52    |
| Moisture of the fuel                | %         | 54.82        | 50.83        |
| Ash content of the fuel             | %         | 1.08         | 1.12         |
| Low calorific value as received     | kJ/kg     | 7290         | 8175         |
| Heat loss:                          | flue gas  | 8.90-9.72    | 7.24-8.66    |
| incomplete combustion               | %         | 0.00-0.02    | 0.00-0.02    |
| carbon                              | %         | 0.49         | 0.25         |
| external (nominal load)             | %         | 1.27         | 1.03         |
| sensible heat of slag               | %         | <0.07        | <0.07        |
| Gross efficiency                    | %         | 87.91-89.25  | 89.62-90.91  |
| Specific fuel consumption           | kg of r.f./GJ | 160.1-162.5 | 157.1-159.4  |
| Emission of CO                      | mg/MJ     | 5-29         | 9-12         |
| Emission of NOx                     | mg/MJ     | 122-131      | 88-92        |

Calibration of the boilers air channels was performed for the following sections: primary air after the air heater in the 1st and 2nd zones; primary air in the 3rd zone; secondary air.

The temperature of the air supplied to the furnace of the boiler had low values: primary air in the 1st and 2nd zones of reciprocating grate - 108–111 °C; primary air in the 3rd zone - 47–49 °C. The temperature of secondary air was \( t_{ba} = 22–25 \) °C and its share in the total amount of organized air supply was \( r_s = 39.0–51.4 \% \) with higher values related to boiler No. 1.

The velocities of the secondary air on exit from the nozzles were 11.9–12.7 m/s (boiler No. 1) and 8.6–10.3 m/s (boiler No. 2). The secondary air provides the after-burning of the combustible components and minimizes the formation of nitrogen oxides. 38–56 % of the total amount of organized air flowed through the air heater. Large levels of the given range refer to the boiler No. 2.

Due to air preheating the temperature in a combustion chamber can be higher than 900 °C which contributes to perfect combustion with a minimum content of harmful substances as well as an increase of efficiency.

Calibration of the boiler flue system was performed for the following sections: gas boiler pass, recirculation line, exit flue. Calibration showed that the velocity fields have the non-uniform profiles. However, the values of the nonuniformity coefficients of the flow velocity distribution for the majority of measuring sections stay within the recommended range of 0.9–1.1 [3]. The exceptions to this are gas ducts to the ash collector and gas recirculation ducts.

The results of the study of velocity fields were used to determine the concentrations of particulate matter in flue gases. The velocities of recycled flue gases on exit from the nozzles were 13.3–14.9 m/s.
(boiler No. 1) and 15.3–20.9 m/s (boiler No. 2). The share of recycled flue gases into the combustion chamber of the boiler No. 2 had large values ($r_{rec} = 0.39–0.42$), its value for boiler No. 1 was $r_{rec} = 0.20–0.29$.

Experimentally obtained values of air inleakage are $\Delta \alpha_f = 0.05$ in the furnace; $\Delta \alpha_{ac} = 0.03–0.04$ in the ash collector; $\Delta \alpha_{ah} = 0.03–0.04$ in the air heater.

While the bark and wood fuel with relative moisture of up to 55 % is burned and the area of reciprocating grate is effectively used, it is possible to ensure a high level of carbon monoxide burnout and its concentration does not exceed 195 mg/Nm$^3$ with $K_{O2} = 6$ %. During the energy survey, the combustion process finished approximately 1.5 m from the end of the reciprocating grate which suggests that there is a reserve for “stretching” the combustion process.

The analysis of the boilers thermal conditions showed that the flue gas heat loss was 7.24–9.72 %. At the same time, higher values of this range refer to boiler No. 1. Rather low level of this loss is explained by small values of air excess in the flue gases $\alpha_{flue} = 1.27–1.52$ and their low temperatures of 139–145 °C.

Heat loss due to fuel incomplete combustion in the studied load range was $q_3 = 0.00–0.02$ % and gross efficiency of the boilers was $\eta_{gross} = 87.91–90.91$ %. At the same time, the boiler No. 2 had higher values of gross efficiency due to its work on bark and wood fuel with less moisture.

For each boilers mode the combustibles content in the slag was 4.95-6.52 % and in the fly ash of 18.75 %, while carbon loss $q_4$ was 0.25-0.49 %.

![Figure 1. The enclosure surface temperatures of the PR-8000 boiler No 1.](image-url)
The boilers are insulated with two layers of mineral wool to reduce heat loss to the environment. The combined relative and calorimetric methods supplemented by thermal imaging were used to determine the external heat loss [3]. The external heat loss amounted to $q_5 = 1.29–1.79\%$ ($q_5^{\text{nom}} = 1.27\%$) for the boiler No. 1 and $q_5 = 1.35–1.62\%$ ($q_5^{\text{nom}} = 1.03\%$) for the boiler No. 2. The example of results of the measurement of the enclosure surface temperature of the boiler’s No. 1 elements at a load of $0.885Q_{\text{nom}}$ are given in Figure 1.

The satisfactory quality of the lining and heat-insulating materials as well as the presence of cooling channels made it possible not only to correct the increased power-to-space ratio for PR-8000 boiler as compared to home boilers [7], but to introduce a downward correction.

Some of the results of thermovision inspection of the hot water boiler No. 1 enclosure surfaces are shown in Figure 2.

The low ash content of the burned fuel ensured a low amount of loss with sensible heat of slag (Table 1).

![Figure 2. Thermal images of the air heater and heat exchanger of PR 8000 boiler No 1.](image)

Emissions of nitrogen oxides had low values of 88–131 mg/MJ (Figure 3c) which is explained by the small furnace air excess and the presence of a three-stage combustion scheme. The range of changes in the emission of carbon monoxide while carrying out the balance experiments was 5.0–29.0 mg/MJ (Figure 3b).

Dust-laden flow sampling from the exit flue leading to the chimney allowed to determine that the particulate matter emission was 26.36–51.60 g/GJ while soot particles emission varied in the range of 1.98–9.64 g/GJ. If we use the conversion constant of 0.14 [8] in determining the content of soot particles with the size of 2.5 $\mu$m or less for the boilers operating on bark and wood fuel with
heterogeneous particle size distribution, the PM 2.5 emission will be 0.277–1.350 g/GJ. This is a good result since according to the [8] the soot particle emission per 1 GJ of fuel heat for wood-fired boilers is 11.0 g/GJ.

**Figure 3.** The histogram of change in efficiency (a), CO emission (b) and NOx (c) from the actual heat output of the PR-8000 boilers No. 1 (top row) and No 2 (bottom row).

The study of the captured particles on the electronic scanning Zeiss SIGMA VP microscope made it possible to determine not only their structure and size, but also the quantitative composition of the elements (Table 2). The study showed that the particles have different shapes: spherical, crystal particles and particles with an amorphous structure. However, particles that are close to spherical shape dominate (Figure 4a). Particles sizes taken in the gas duct to the ash collector varied from 10 nm to 160 μm.

**Figure 4.** Particulate matter taken from the flue duct to the ash collector.

A significant amount of recirculated gases reduces the temperature level especially in the combustion chamber of boiler No. 2 and causes the removal of unburned wood particles outside. So in
the particles taken from the gas flow to the ash collector there are small quantities of wood particles with a size of up to 160 μm that have passed only the initial stage of thermal decomposition and combustion, while the pores are still visible on the walls of tracheids (Figure 4b). The carbon content in them reaches 80 %. Due to the low density and high windage the trapping in the inertial-type ash collectors is inefficient, therefore, char particles are also contained in a small quantity in the combustion products entering the chimney after the ash collector (Figure 5).

![Figure 5. Particulate matter taken from the gas duct after the ash collector.](image)

The sizes of the particles taken from the flue duct after the ash collector were in the range from 10 nm to 110 μm while particles of 20-50 nm in the shape close to spherical dominated (Figure 5). The elemental composition on a dry mass of the collected particles varies significantly, therefore it is shown in the form of a range in Table 2.

| Element | Content, % |
|---------|------------|
| C       | 14.0 – 80.0 |
| O       | 19.5 – 54.8 |
| Ca      | 2.3 – 27.7 |
| Si      | 0.1 – 27.1 |
| Cu      | 0.0 – 0.6  |
| Fe      | 0.1 – 0.7  |
| Mg      | 0.1 – 1.0  |
| Mn      | 0.0 – 0.8  |
| K       | 0.4 – 2.6  |
| Zn      | 0.0 – 0.6  |

The concentrations of PM in combustion products going to the chimneys were 93.6 mg/nm³ for boiler No. 1 with a load of 88.8 % of the nominal and 54.32 mg/nm³ for boiler No. 2 with a load of 74.0 % of the nominal.

The conducted research allowed determining the values of the overall flue gas cleaning efficiency during its passage through the ash collector and the air heater which amounted to 65.5–74.1 %.
5. Conclusions
The design characteristics of the main and auxiliary equipment of the boiler house of SJSC “Sawmill 25” provide sufficiently high economic and environmental performance when the bark and wood fuel with relative moisture of up to 55 % is burned and the areas of the reciprocating grates is effectively used and drafts in the combustion chambers is close to optimal values. In the studied load range (63.0–98.4 % of the nominal) the gross efficiency was 87.91–90.91 % while the harmful substances emissions had the following values: \( E_{\text{NOx}} = 88–131 \); \( E_{\text{CO}} = 5–29 \); \( E_{\text{PM}} = 26.36–51.60 \); \( E_{\text{SOx}} = 1.98–9.64 \) mg/MJ.

With higher moisture of the burned fuel there are draft restrictions because of no reserve of flue-gas fan capacity. A reduction of recirculation of exhausted flue gas within tolerable limits; additional setting of automated control system to reduce the lower permissible threshold of oxygen concentration in the exit flue gas; ensuring an optimal range of draft in the combustion chambers in all the operation modes of the boilers; maximum use of the areas of reciprocating grates in the combustion process are required for partial or complete lifting of restrictions on burning bark and wood fuel with a relative moisture of more than 55 %.

Excessive supply of recycled gas causes a decrease in the temperature level in the combustion chambers and ballasting with water vapor. Taking into account that in studied load range the temperature of the flue gas after the furnaces was 852–937 °C there is no need to keep the proportion of recirculation of combustion products more than 0,35 as it increases the costs associated with own needs and reduces net boilers efficiency.

Implementation of all recommendations will reduce the power consumption for own needs and create prerequisites for stabilization of the combustion process during the burning of high-moisture fuel.

The use of biofuels in automated boilers as a part of energy sources is a relevant and promising direction for both regional and state policies.

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