The energy and ecological performance of the hot water boiler burning linden bark and wood briquettes

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Abstract. The North-West of Russia possesses huge wood resources reserves, therefore the issues of the most efficient use of wood biomass are relevant for this region. The implication of wood biofuels into fuel and energy budget provides an opportunity to reduce the negative impact of power industry facilities on the environment and preserve the potential of non-renewable fuels for future generations. An effective way of the complex solution of energy and ecological problems, while providing heating loads for consumers, is the use of modern devices operating on solid biofuel. Technical analysis of foreign and domestic high-performance heating units has great importance. The aim of the research is an evaluation of energy and ecological performance of the Firematic 60 hot water boiler burning bark of linden, briquettes from wood sanding dust and sawdust of plywood processing, as well as briquettes obtained by pressing softwood sawdust and shavings. The paper presents thermotechnical characteristics of burning biofuels and the components of boiler heat balance and gaseous emission from the burning linden bark and briquettes. Particulate matter emission and content of soot were studied. The shape and composition of soot particles were determined with a Zeiss SIGMA VP electronic scanning microscope. Presented data were obtained using equipment of the Research Center of Power Engineering Innovations. The results of the comprehensive energy audit have shown that the Firematic 60 boiler provides high technical and economic performance with minimum emission of harmful substances to the atmosphere. It can be used for low-rise buildings heat supply in weather conditions of the Arctic region especially.

1. Introduction

One of priority areas of power industry development is the use of renewable energy resources (RER). Such sources include wood biomass the use of which in regions with the developed timber industry complex is a promising solution to ensure their energy independence. In addition, the energy use of wood biomass makes it possible to ensure the utilization of by-products of logging and woodworking enterprises, to obtain cheaper energy, to reduce the harmful effects on the environment, etc [1-4].

Experiments were carried out at the building of Educational and Scientific Center of Power Engineering Innovations of NArFU named after M.V. Lomonosov which is connected to the district heat supply system. Reserve heat supply source is Austrian “Firematic 60” boiler of Herz Energitechnik GmbH which is also used to provide laboratorial sessions and researches. The boiler is designed to operate on wood pellets and chips [5]. According to the manufacturer the boiler nominal capacity (60 KW) is achieved while burning biofuel with specific moisture of $W_t < 25 \%$. The operational principle of the boiler is presented in [6].
2. Experimental procedure

Comprehensive study of boiler operational performance was carried out at 3 stages. In the course of the first stage boiler balance experiments were carried out while a combustion chamber was fed by briquettes (Table 1, tests No. 1,2) obtained from fine by-products of plywood factory which were previously divided into parts that meet the requirements of the fuel supply system during its operation on chips. During the second stage of testing the boiler operated on the linden bark (tests No. 3,4) grain size distribution of which is shown in Figure 1. At the third stage of testing briquettes of sawmill production were burned in the boiler furnace (tests No. 5,6) obtained by pressing coniferous sawdust and shavings.

The analysis of fuels was carried out with armamentarium of thermal analysis laboratory and IKA C2000 basic Version 2 calorimeter with LOIP FT-216-25 liquid cryothermostat. Study of the grain-size distribution of fuel composition and combustion residues was carried out with \( \text{AS200} \) sieve shakers. The determination of velocity fields and flue gas flows was performed with a Pitot tube and a micromanometer of Testo-435 precision instrument. The results of velocity fields study were used to determine the particulate matter concentrations at the flue gas after the boiler. In order to achieve that it was used external filtration method which is applied via a OP-442 TC impactor, a dust sampling probe, a filter holder, etc. A Testo 350XL gas analyzer was used to determine content of combustion products. Fuel consumption was determined by the equation of the indirect heating balance. Experimental data analysis was performed using multiblock program-methodological complex [5]. The main results of energy survey of the Firematic 60 boiler are presented in Table 1.

After an automatic start-up of the boiler the period it takes to reach the rated load does not exceed 20 minutes. After 33-38 minutes an automated control system provides inlet boiler water temperature close to the optimum value (60 °C).

| Value                        | Symbol, dimension | No.1   | No.2   | No.3   | No.4   | No.5   | No.6   |
|------------------------------|-------------------|--------|--------|--------|--------|--------|--------|
| Heat capacity                | \( Q \), KW       | 75.6   | 56.4   | 53.4   | 71.1   | 57.3   | 79.8   |
| Outlet operating pressure of the water | \( P_{o.p.} \), MPa | 0.38   | 0.38   | 0.40   | 0.40   | 0.19   | 0.19   |
| Outlet water temperature     | \( T_{o.w.} \), °C | 78.0   | 81.0   | 78.0   | 83.0   | 78.0   | 75.0   |
| Moisture of fuel             | \( W_t \), %      | 5.05   | 11.02  | 11.27  | 11.27  | 11.27  | 11.27  |
| Ash content of fuel          | \( A_r \), %      | 0.47   | 3.02   | 0.36   | 0.36   | 0.36   | 0.36   |
| Volatile yield               | \( V_{daf} \), %  | 83.2   | 80.1   | 83.20  | 83.20  | 83.20  | 83.20  |
| Lower calorific value        | \( Q'_l \), MJ/kg | 17.16  | 16.90  | 16.71  | 16.71  | 16.71  | 16.71  |
| Flue gas temperature         | \( \theta_{f.g.} \), °C | 169    | 149    | 131    | 157    | 133    | 140    |
| Excess air in flue gas        | \( \alpha_{f.g.} \) | 1.59   | 1.68   | 1.51   | 1.47   | 1.45   | 1.35   |
| Heat loss:                   |                   |        |        |        |        |        |        |
| flue gas                     | \( q_2 \), %      | 9.26   | 8.30   | 5.88   | 7.23   | 6.11   | 6.16   |
| incomplete combustion        | \( q_3 \), %      | 0.02   | 0.05   | 0.04   | 0.03   | 0.01   | 0.02   |
| carbon                       | \( q_4 \), %      | 0.24   | 0.24   | 1.23   | 1.23   | 0.36   | 0.36   |
| external                     | \( q_5 \), %      | 0.40   | 0.53   | 0.56   | 0.42   | 0.52   | 0.38   |
| sensible heat of slag        | \( q_6 \), %      | 0.01   | 0.01   | 0.08   | 0.08   | 0.01   | 0.01   |
| Gross efficiency of the boiler | \( \eta_{gross} \), % | 90.08  | 90.87  | 92.20  | 91.01  | 92.99  | 93.09  |
| Total fuel consumption       | \( B \), kg/h     | 18     | 13     | 12     | 17     | 13     | 18     |
| Emission of NO\(_x\)         | \( \text{NO}_x \), mg/MJ | 163    | 176    | 214    | 240    | 71     | 62     |
| Emission of CO               | \( \text{CO} \), mg/MJ | 18     | 57     | 45     | 33     | 13     | 17     |
The analysis of thermal conditions has shown that heat loss with flue gas is $q_2 = 5.88 - 9.26\%$, but it rises when load and inlet boiler water temperature increases.

A stage fuel combustion scheme and efficient mixing of secondary air with combustible components of fuel while keeping the excess air coefficient in furnace within the range $1.35 - 1.68$ allow to reach low values of heat loss due to incomplete fuel combustion. Values of carbon oxide concentrations corrected to excess air coefficient of 1.4 are 37.5-112.5 mg/Nm$^3$.

Carbon loss when boiler operates on briquettes (Table 1, tests No.1,2 and No. 5,6) had a very low level which can be explained by higher uniformity of the grain size distribution of fuel, its low ash content, and also a rather high calorific value. These factors ensured a high degree of burnout of combustible components in focal residues. In contrast with briquettes linden bark has a higher ash content and a less uniformity of the grain size distribution which caused an increase of carbon loss, while the content of combustible in fly ash and slag was $C_{c,\text{ash}} = 45.64\%$, $C_{c,\text{slag}} = 5.15\%$ respectively.

When the combustion products reverse after the first path in fire tubes particulate matter with predominant dimensions of 125 μm and larger are separated into ash pit from where removed in a collection bin. The grain size distribution of focal residues selected from ash pits of the combustion chamber and the heat exchanger when burning briquettes is shown in Figure 2.

Experimental studies have shown that the design of the boiler makes it possible to ensure sufficiently efficient combustion of both pressed wood sanding dust and sawdust from the plywood trimming line (Table 1, tests No. 1.2) as well as pressed sawdust and shavings of sawmill plant (Table
1, tests No. 5.6). However, in the process of feeding the pressed material to the combustion chamber, its partial destruction occurs which increases the emissions of particulate matter into the atmosphere.

Loss with sensible heat of slag during the boiler operation on pressed plywood and sawmill wastes did not exceed $q_6 = 0.01\%$; and when burning linden bark $q_6 = 0.08\%$.

External heat loss for rated loads is determined with master curves [7] for domestic heating devices with carrying out check and engineering calculation as well as standard tests. Validity of appliance of master curves for the foreign devices [7] should be proved experimentally. The amended approach was elaborated for determination of external heat loss. This approach is based on the combined use of the relative and calorimetric methods supplemented with thermal imaging [5]. Experimental studies have shown that external heat loss for rated load (60 KW) of the boiler does not exceed 0.6\% that is significantly lower in comparison with Russian standards [7]. Low values of this loss are explained by moderate overall dimensions of the boiler and high quality of lining and thermostimulation materials.

Greater efficiency values were achieved for sawmill briquettes than plywood briquettes despite the higher moisture (2.23 times). In addition, the minimum emissions of nitrogen oxides and carbon monoxide were achieved when the boiler operated on pressed sawmill waste.

Low emission of nitrogen oxides during the combustion of all types of biofuels can be explained by a moderate level of maximum temperatures and excess air in the burner and the afterburner as well as two-stage combustion scheme. Sulphur dioxide was absent in combustion products of biofuels on all modes of the boiler operation.

The stage combustion scheme and intensive mixing of secondary air with combustible components of fuel allow to provide highly efficient operation of the boiler in the condition of low oxygen concentration of 4.0-6.0\%. As oxygen concentration increases by more than 6\% the emission of harmful substances to the atmosphere rises too. To that end the threshold value of oxygen concentration should be reduced to 4\% in the automated control system.

The results of studies of soot particles emission with the use of external filtration method under isokinetic conditions of gas extraction [8] and determine of soot particles content by the method [9] have shown that soot emission factor is 5.23–5.34 g (heat output of 57.3–79.8 KW) per 1 GJ of heat of sawmill plant briquette. The average emission factor PM2.5 (the conversion constant of 0.14 [10]) is 0.74 g/GJ. For comparison, the average soot emission factor for Arimax Bio Energy boilers with a nominal capacity of 1.5 MW operating on wood pellets and equipped with inertial ash collectors amounted to 5.75 g/GJ, and emissions factor PM2.5 - 0.805 g/GJ.

The captured particles were studied by the electronic scanning Vega 3 Tescan microscope. In this case, a fragment of a filter with an area of 478 × 478 μm was analyzed. Figure 3 shows the distribution of particles by equivalent diameter, as well as the distribution of particles depending on the aspect ratio (the ratio of the particle length to the equivalent diameter) in Figure 4.
Studies have shown when the boiler operating on briquettes obtained from coniferous sawdust and shavings, particles with an aspect ratio of 1.2–2 (Fig. 4) are predominantly emitted into the atmosphere with flue gases, accounting for 83.7% of the total number of particles. The number of particles having the shape close to the correct and the aspect ratio of ~ 1 is 2.1%. Particles with an aspect ratio of more than 4 are missed.

For two another fuels the captured particles were studied by the electronic scanning Zeiss SIGMA VP (Carl Zeiss) microscope. In selected samples during burning the plywood plant briquettes three main types of particles have been identified: spherical shape, solid crystal particles and particles with an amorphous structure [11,12].

In samples obtained by burning bark, crystalline particles of prismatic and lamellar shapes predominate (Fig. 5), their size is in the range from 100 nm to 1.5 μm. The chemical composition of these particles, %: carbon - 26.4...25; chlorine - 27...28; potassium - 19...24; sodium — 0.6...0.7; oxygen - 18...25; sulfur – 3...4; silicon - 0.1..0.4.

Figure 5. The structure of the particles of ash produced during the burning of linden bark.

The obtained results have shown that particles with dimension less than 13 μm are predominantly carried away to the atmosphere [11,12].

3. Conclusion
A comprehensive energy survey has shown that the Firematic 60 boiler provides high technical and economic performance and minimum emissions of harmful substances to the atmosphere while combusting biofuels. It should be used for low-rise buildings heat supply in weather conditions of the Arctic region especially.

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