Study of the energy efficiency of wood pellets and poplar chips

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Abstract. Poplar is the most common type of fast-growing tree species of great economic and industrial importance. Therefore, determining the effectiveness of its energy use is an important task. A study of the operational efficiency of the Firematic 60 boiler when working on poplar chips, as well as pine wood pellets with a diameter of 6 mm and spruce wood pellets with a diameter of 8 mm was carried out. The elemental composition of burned fuels and residues was studied using an EDX-8000 X-ray fluorescence spectrometer and a Euro EA-3000 analyzer. The components of the heat balance and emission of harmful substances were determined. The emissions of particulate matter and the content of soot particles were studied. The shape and composition of soot particles were determined using a Zeiss SIGMA VP electronic scanning microscope. An energy examination showed that the boiler provides high technical and economic indicators and minimal emissions of harmful substances into the environment when burning wood pellets and poplar chips.

1. Introduction
One of the priority areas of energy development is the use of renewable energy sources. These sources include woody biomass. Amid growing interest in the energy use of by-products of logging and woodworking enterprises, much attention should be paid to fast-growing plantings. Since they make it possible to compensate for periods of intensive forest use and to maintain for many years a balance between consumption and restoration of wood mass. The most common type of fast-growing tree species of great economic and industrial importance is poplar. Therefore, determining the effectiveness of its energy use is an important task [1].

Research work was carried out in the Educational and Scientific Center for Power Engineering Innovations of the Higher School of Power Engineering, Oil and Gas connected to the district heating system. Reserve source of heat supply to the building is the Firematic 60 boiler by the Austrian company Herz Energietechnik GmbH which is also used in the implementation of laboratory works and research. The boiler is designed for burning wood pellets and chips [2]. According to the manufacturer, the rated boiler power (60 kW) is ensured when operating on biofuels with a related moisture of $W^r_{17} \leq 25\%$. The design and principle of operation of the boiler are considered in the paper [3].
2. Results and discussion
A comprehensive study of the efficiency of the boiler was carried out in three stages. During the first stage, balance tests were carried out when burning wood pellets with a diameter of 6 mm produced by Region-Les LLC (Table 1, test No. 1). At the second stage, the boiler worked on wood pellets with a diameter of 8 mm produced by CJSC Lesozavod 25 (Table 1, test No. 2). During the third stage of the energy inspection, poplar chips were burned in the boiler furnace (Table 1, tests No. 3, 4), the grain size distribution of which is shown in Figure 1. The analysis of fuels was carried out with equipment of thermal analysis lab and IKA C2000 basic Version 2 calorimeter and LOIP-FT-216-25 cryothermostat. The elemental composition of the burned fuels and combustion residues was carried out with AS200 and Microtrac S3500 sieve shakers. The determination of velocity fields and flue gas flows was performed with a Pitot tube and micromanometer of Testo-435 precision instrument. In order to determine the particulate matter concentrations at the flue gas after the boiler was used external filtration method which is applied via an 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 inverse heat balance equation. Processing of experimental data was carried out using a multi-module software and methodological complex [1], the main research results are given in Table 1.

| Value                                    | Symbol, dimension | Tests |
|------------------------------------------|-------------------|-------|
| Heat capacity                            | $Q$, kW           | 67.0  | 88.2 | 94.0 | 103.3 |
| Outlet operating pressure of the water   | $P_{op}$, MPa     | 0.15  | 0.17 | 0.19 | 0.25  |
| Outlet water temperature                 | $t_{ow}$, °C      | 78.0  | 81.5 | 81.0 | 83.0  |
| Moisture of fuel                         | $W'$, %           | 7.26  | 7.13 | 9.62 |
| Ash content of fuel                      | $A'$, %           | 0.65  | 0.70 | 1.85 |
| Volatile yield                           | $V_{daf}$, %      | 84.41 | 83.93| 84.17|
| Low calorific value                      | $Q'$, MJ/kg       | 17.22 | 17.28| 16.71|
| Flue gas temperature                     | $g_{fg}$, °C      | 146.3 | 150.0| 159.0| 164.5|
| Excess air in flue gas                   | $\alpha_{fg}$     | 1.45  | 1.35 | 1.32 | 1.30  |
| Heat loss:                               |                   |       |      |      |
| flue gas                                 | $q_{2}$, %        | 6.90  | 6.70 | 7.09 | 7.30  |
| incomplete combustion                    | $q_{3}$, %        | 0.01  | 0.00 | 0.05 | 0.04  |
| carbon                                   | $q_{4}$, %        | 0.24  | 0.26 | 0.71 | 0.71  |
| external                                 | $q_{5}$, %        | 0.45  | 0.34 | 0.32 | 0.29  |
| Gross efficiency of the boiler           | $\eta_{gross}$, % | 92.39 | 92.68| 91.79| 91.61|
| Total fuel consumption                   | $B$, kg/h         | 15.0  | 20.0 | 22.0 | 24.0  |
| Emission of NO$_x$                       | NO$_x$, mg/MJ     | 52.0  | 47.0 | 66.0 | 79.0  |
| Emission of CO                           | CO, mg/MJ         | 9.0   | 5.0  | 55.0 | 45.0  |
| Particulate matter emission              | PM, mg/MJ         | 7.25  | 7.03 | 12.91| 12.88 |

The analysis of fuels showed that dry and ash free low calorific value of poplar and its bark not inferior to spruce and pine. However, the lower calorific value for dry weight of poplar and its bark is slightly less, due to the higher ash content. Elemental analysis showed that poplar is characterized by a lower carbon content, but a higher hydrogen content in comparison with spruce and pine (Table 2). Woody biomass contains very small amounts of heavy metals, but most of them are higher in poplar than in spruce and pine. This may be due to the growth of poplar in the urban area of an industrialized
city. During the combustion of wood biomass, the concentrations of heavy metals in ash have higher values, while the degree of concentration for different elements varies greatly (Table 2).

![Grain size distribution of poplar chips](image)

**Figure 1.** Grain size distribution of poplar chips.

**Table 2.** Elemental composition of burned fuels and their ashes on a dry weight, %.

| Element    | Test fuels and residues |  |  |  |  |  |
|------------|-------------------------|---|---|---|---|---|
|            | Pine pellets | Spruce pellets | Pine ash | Spruce ash | Poplar wood | Poplar bark |
| Strontium  | 0.0007       | 0.0007       | 0.195     | 0.213      | 0.003       | 0.037       |
| Zinc       | 0.0056       | 0.0046       | 0.0723    | 0.135      | 0.019       | 0.156       |
| Cuprum     | 0.109        | 0.0834       | 0.360     | 0.197      | 0.073       | 0.007       |
| Nickel     | 0.0105       | 0.0088       | 0.0134    | 0.0149     | 0.0109      | 0.005       |
| Ferrum     | 0.338        | 0.427        | 1.563     | 2.424      | 0.269       | 0.280       |
| Manganese  | 0.0274       | 0.0266       | 3.589     | 2.489      | 0.003       | 0.013       |
| Chromium   | 0.0029       | 0.0014       | 0.0255    | 0.0748     | 0.006       | 0.011       |
| Calcium    | 0.301        | 0.278        | 35.482    | 35.093     | 0.761       | 5.16        |
| Potassium  | 0.133        | 0.132        | 9.292     | 7.441      | 0.428       | 1.04        |
| Chlorine   | -            | -            | 0.419     | 0.434      | -           | 0.004       |
| Sulfur     | 0.118        | 0.120        | 2.297     | 2.225      | 0.083       | 0.269       |
| Phosphorus | 0.0086       | 0.0074       | 0.527     | 0.810      | 0.033       | 0.240       |
| Silicon    | 0.0381       | 0.0396       | 2.142     | 2.448      | 0.145       | 0.582       |
| Aluminium  | 0.0445       | 0.0442       | 0.508     | 0.561      | 0.054       | 0.160       |
| Magnesium  | 0.0314       | 0.0516       | 3.519     | 3.727      | 0.109       | 0.276       |
| Sodium     | 0.595        | 0.616        | 0.674     | 1.028      | 0.051       | 0.092       |
| Oxygen     | 40.534       | 40.404       | 29.279    | 30.485     | 42.1        | 34.4        |
| Carbon     | 50.224       | 50.184       | 9.375     | 9.578      | 47.5        | 49.3        |
| Hydrogen   | 7.185        | 7.330        | -         | -          | 8.048       | 7.760       |
| Nitrogen   | 0.209        | 0.195        | -         | -          | 0.200       | 0.170       |
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).

The analysis of thermal conditions showed that heat loss with flue gas is \( q_2 = 6.7–7.3\% \), 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 1.30-1.45 allowed to reach low values of heat loss due to incomplete fuel combustion (no more than 0.05%). Values of carbon oxide concentrations corrected to excess air coefficient of 1.4 are 13.3–139.2 mg/Nm³.

Carbon losses when boiler operates on pellets with the diameters of 6 or 8 mm were very low (respectively 0.24 and 0.26 %) due to the uniformity of the grain size distribution of the fuel, its low ash content, and a sufficiently high calorific value. These factors ensured a high completeness of burning of combustible components in ash residues. The content of combustible components in fly ash from the furnace, as well as in the slag during the burning of wood pellets, were \( C_{ash} = 41.17–41.26\% \) and \( C_{slag} = 6.34–6.43\% \). Poplar chips, unlike granules, have a higher ash content and a less uniform grain size distribution. This caused an increase in carbon loss, while the content of combustible components in fly ash and slag amounted to \( C_{ash} = 41.69\% \), \( C_{slag} = 6.15\% \).

Grain size distribution of ash residues taken from an ash box and a heat exchanger when burning poplar bark is shown in Figure 2.

![Figure 2. Grain size distribution of ash residues after burning poplar bark: 1 – ash box; 2 – heat exchanger.](image)

Particulate matter at a 180° turn of the combustion products after the first pass in the fire tubes, mainly with a particle size of 125 microns or more, is separated into an ash box, from where it is removed by a screw into an ash bin. Fractional analysis showed that the largest number of combustible components is contained in particles with a size of 0.5 mm or more (Figure 3a). An analysis of the experimental data, taking into account the mass content of different fractions, showed that the decisive share in carbon loss is exerted by the underburning of combustible components in particles with a size of 125 <\( x < 1000 \) μm (Figure 3b).

Experimental studies have shown that the design of the boiler allows for efficient burning of both wood pellets and poplar chips. To determine the external heat loss, an amended approach was used, based on a combination of relative and calorimetric methods supplemented with thermal imaging [2]. Experimental studies have shown that external heat loss for rated load (60 KW) of the boiler does not exceed 0.5 % that is significantly lower in comparison with Russian standards [4]. Low values of this loss are explained by moderate overall dimensions of the boiler and high quality of lining and thermoinsulation materials.
Figure 3. Content of combustible components in fly ash separated into the heat exchanger when burning poplar chips: a – fractional distribution; b - concentration of combustible components taking into account weight percentage of different fractions.

Losses due to temperature of bottom ash while the boiler operates on wood pellets did not exceed $q_6 = 0.02\%$ and poplar chips - $q_6 = 0.05\%$.

The gross boiler efficiency when working on wood pellets was higher than when burning poplar chips, despite the higher values of the excess air coefficients in the flue gases. This is due to the higher thermotechnical characteristics of pellets. At the same time, when burning wood pellets with a diameter of 8 mm, the minimal emissions of nitrogen oxides and carbon monoxide were achieved.

Low emission of NO$_x$ for each fuel is explained by moderate level of maximum temperatures and excess air in burner and afterburner as well as two-stage combustion scheme. Sulfur dioxide in the combustion products during the burning of biofuels was absent in all modes of operation of the boiler.

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 research of soot particles emission with the use of external filtration method [5] under isokinetic conditions of gas extraction [6] have shown that soot emission factor when burning 6 mm pellets was 2.99 g/GJ. The average PM2.5 emission factor (with a conversion coefficient of 0.14 [7]) was 0.419 g/GJ. As a comparison, the average soot emission factor for Arimax Bio Energy boilers with a nominal power of 1.5 MW, operating on wood pellets and equipped with inertial ash collectors, was 5.75 g/GJ, and PM2.5 emission factor – 0.805 g/GJ.

When the boiler operates on 8 mm pellets soot emission factor remained at about the same level of 2.89 g/GJ. The PM2.5 emission factor was 0.405 g/GJ. The transition to the burning of poplar chips was accompanied by an increase in soot emission factor to 5.376 g/GJ and, accordingly, PM2.5 emission factor to 0.753 g/GJ.

In the experiments, particulate sampling was carried out from the gas flue before chimney of Firematic 60 boiler operating on poplar chips. The sampled particles were studied by the electronic scanning Zeiss SIGMA VP (Carl Zeiss) microscope. Particulate samples for study were on air filters (Figure 4). Microphotographs of fly ash were used to construct histograms of the distribution of microparticles and to determine the weight fractions (Figure 5).

An analysis of the data showed that a 180º turn of the combustion products after the first pass in the fire tubes allows the gas to be cleaned of particulate matter with a size of more than 40 microns. Particles with a size of less than 10 microns prevail when burning poplar chips in the flue gas in a quantitative ratio, and the largest weight content falls on particles with a size of 30 to 40 microns.
81.3% of particles in fly ash have a shape close to regular (ratio of length to equivalent diameter is ~ 1).

Figure 4. The structure of particulate matter formed during the burning of poplar chips.

Figure 5. Microparticles in flue gas when burning poplar chips: a – quantity distribution and weight content of particles with different sizes; b – quantity distribution of particles by shape (ratio of length to equivalent diameter).

3. Conclusion
Dry and ash free low calorific value of poplar and its bark not inferior to spruce and pine. However, the lower calorific value for dry weight of poplar and its bark is slightly less, due to the higher ash content. Poplar is characterized by a lower carbon content, but a higher hydrogen content in comparison with spruce and pine.

An energy tests showed that Firematic 60 boiler provides high technical and economic performance and minimal emissions of harmful substances into the environment when burning wood pellets and poplar chips. Within this framework, fast-growing poplar wood should acquire worthy economic and industrial importance as an effective biofuel.

References
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