Energy producing effectiveness study: larch and poplar chips, wood pellets

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Abstract. Larch is one of the most valuable species of conifers. Its wood is widely used in many sectors of the economy. Therefore, determining the efficiency of energy use of by-products of processing of larch, as well as fast-growing wood species, which include poplar, is an important task. A study of the operational efficiency of the Firematic 60 boiler when working on larch and poplar chips, as well as spruce wood pellets with a diameter 6 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. The energy tests showed that the boiler provides high technical and economic indicators and minimal emissions of harmful substances into the environment when burning larch and poplar chips, wood pellets.

1. Introduction
One of the priority areas of energy development is the use of renewable energy sources. These sources include woody biomass [1]. In Russia, larch forests rank first in terms of forested area - 258 million hectares (about 40%) with a total timber stock of over 26 billion m$^3$. A unique feature of larch wood is its high density and natural biostability, due to which it is widely used in the forestry complex as lumber, in the production of furniture, plywood, in housing construction, etc. [2-3]. Despite the development of technologies and techniques, large volumes of wood waste are generated in the process of logging and woodworking. The energy use of woody biomass allows for their utilization, obtain cheaper energy and reduce the harmful impact on the environment [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 [4]. According to the manufacturer, the rated boiler power (60 kW) is ensured when operating on biofuels with a related moisture of $W_r \leq 25\%$. The design and principle of operation of the boiler are considered in the paper [5].
2. Materials and Methods
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 larch chips (Table 1, tests No. 1,2). At the second stage, the boiler worked on poplar chips (Table 1, tests No. 3,4). During the third stage of the energy inspection, spruce wood pellets with a diameter of 6 mm were burned in the boiler furnace (Table 1, tests No. 5,6). 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 residues was studied using an EDX-8000 X-ray fluorescence spectrometer and a Euro EA-3000 analyzer. The procedure for fractionating of fuel and combustion residues was carried out using sieve shakers "029" and AS200 Control. The cross-sections of the gas ducts were calibrated using Pitot tube and micromanometer of Testo-435 precision instrument. Based on the results of studying the velocity fields, the concentration of solid particles in the flue gases after the boiler was determined. In this case, external filtration method was used 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. Samples of soot and ash particles were taken from the gas duct to the chimney using the external filtration method under isokinetic conditions. The captured particles were examined with a Zeiss SIGMA VP scanning electron microscope (Carl Zeiss). Processing of experimental data was carried out using a multi-module software and methodological complex [1].

3. Results
The main research results are given in table 1. For each type of fuel, the results of only two experiments are given, reflecting the obtained energy-ecological indicators of the boiler operation. The analysis of fuels showed that as dry and ash free low calorific value as dry low calorific value of larch chips not inferior to spruce wood pellets. The low calorific value for dry and ash free weight of poplar and its bark is close to the values obtained for spruce, however, in terms of the low calorific value for dry weight, poplar and its bark is inferior due to the higher ash content. Elemental analysis showed that poplar and larch are characterized by a lower carbon content, but a higher hydrogen content in comparison with spruce (Table 2). Larch bark has an increased carbon content, which determined its higher low calorific value. Woody biomass contains very small amounts of heavy metals, but most of them are higher in poplar than in larch and spruce [6]. 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).

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 grain size distribution of the focal residues taken from the ashpits of the furnace and the heat exchanger during the combustion of larch and poplar chips is shown in figure 1.

![Figure 1](image-url)  
**Figure 1.** The grain size distribution of the focal residues of: 1 – larch chips; 2 – poplar chips taken from the ashpits of: a – the furnace; b – the heat exchanger.
## Table 1. The main performance of the boiler burning larch and poplar chips, wood pellets.

| Value                        | Symbol, dimension | Tests          |
|------------------------------|-------------------|----------------|
|                              |                   | No. 1 | No. 2 | No. 3 | No. 4 | No. 5 | No. 6 |
| Heat capacity                | $Q$, kW           | 74.0  | 68.5  | 94.0  | 103.3 | 71.3  | 83.5  |
| Outlet operating pressure of | $P_{opr}$, MPa    | 0.30  | 0.33  | 0.19  | 0.25  | 2.2   | 2.4   |
| the water                    |                   | 81.0  | 79.0  | 81.0  | 83.0  | 78.0  | 78.0  |
| Outlet water temperature     | $t_{ow}$, °C      | 0.30  | 0.33  | 0.19  | 0.25  | 2.2   | 2.4   |
| Moisture of fuel             | $W'$, %           | 9.71  | 9.62  | 8.60  | 8.60  |       |       |
| Ash content of fuel          | $A'$, %           | 0.35  | 1.85  | 0.43  | 0.43  |       |       |
| Volatile yield               | $V_{daf}$, %      | 80.93 | 84.17 | 84.75 |       |       |       |
| Low calorific value          | $Q_0$, MJ/kg      | 16.84 | 16.71 | 16.97 |       |       |       |
| Flue gas temperature         | $\theta_{fg}$, °C | 155   | 140   | 159.0 | 164.5 | 154   | 155   |
| Excess air in flue gas       | $\alpha_{fg}$     | 1.40  | 1.45  | 1.32  | 1.30  | 1.46  | 1.43  |
| Heat loss:                   |                   |       |       |       |       |       |       |
| flue gas                     | $q_2$, %          | 7.30  | 6.61  | 7.09  | 7.30  | 7.68  | 7.61  |
| incomplete combustion        | $q_3$, %          | 0.00  | 0.03  | 0.05  | 0.04  | 0.01  | 0.01  |
| carbon                       | $q_4$, %          | 0.20  | 0.20  | 0.71  | 0.71  | 0.22  | 0.22  |
| external                     | $q_5$, %          | 0.41  | 0.44  | 0.32  | 0.29  | 0.42  | 0.36  |
| Gross efficiency of the boiler | $\eta_{gross}$, % | 92.09 | 92.71 | 91.79 | 91.61 | 91.67 | 91.80 |
| Total fuel consumption       | $B$, kg/h         | 17.0  | 16.0  | 22.0  | 24.0  | 16.0  | 19.0  |
| Emission of NO               | $NO_x$, mg/MJ     | 76.0  | 74.0  | 66.0  | 79.0  | 56.0  | 54.0  |
| Emission of CO               | $CO$, mg/MJ       | 5.0   | 35.0  | 55.0  | 45.0  | 6.0   | 6.0   |
| Particulate matter emission  | PM, mg/MJ         | 22.03 | -     | 12.91 | 12.88 | 4.84  | 4.39  |

Particulate matter at a 180° turn of the combustion products after the first pass in the fire tubes is separated into an ashpit, from where it is removed by a screw into an ash bin. Fly ash obtained from burning larch chips taken from under the heat exchanger has a high degree of composition heterogeneity ($n = 1.033$) and a noticeably coarse dispersed composition ($b = 0.0005$). Moreover, it is dominated by particles with a size of 0.25 mm or more, the weight content of which is 89.09%. Fractional analysis showed that the highest content of combustible components is contained in particles with a size of 0.5 mm or more (Figure 2a). An analysis of the experimental data, taking into account the mass content of different fractions, showed that unburnt fuel components in the particles size of over 500 microns (Figure 2b) has a crucial interest in carbon loss.

![Figure 2](image-url)
Table 2. Elemental composition of burned fuels and their ashes on a dry weight, %.

| Element     | Test fuels and residues |   |   |   |   |
|-------------|-------------------------|---|---|---|---|
|             | Larch wood | Larch ash | Larch bark | Ash of larch bark | Poplar wood | Poplar bark |
| Barium      | 0.001       | 0.265     | 0.002      | 0.122             | 0.002       | 0.006       |
| Strontium   | 0.001       | 0.315     | 0.004      | 0.319             | 0.003       | 0.037       |
| Zinc        | 0.002       | 0.076     | 0.005      | 0.221             | 0.019       | 0.156       |
| Cuprum      | 0.003       | 0.036     | 0.003      | 0.025             | 0.073       | 0.007       |
| Nickel      | -           | -         | -          | -                 | 0.109       | 0.005       |
| Ferrum      | 0.019       | 2.64      | 0.027      | 0.772             | 0.269       | 0.280       |
| Manganese   | 0.003       | 0.999     | 0.047      | 1.12              | 0.003       | 0.013       |
| Chromium    | -           | -         | -          | -                 | 0.006       | 0.011       |
| Titanium    | 0.001       | 0.210     | 0.004      | 0.138             | 0.002       | 0.015       |
| Calcium     | 0.072       | 26.4      | 0.674      | 25.4              | 0.761       | 5.16        |
| Potassium   | 0.051       | 9.19      | 0.174      | 5.47              | 0.428       | 1.04        |
| Chlorine    | -           | -         | -          | -                 | -           | 0.004       |
| Sulfur      | 0.010       | 1.07      | 0.040      | 0.582             | 0.083       | 0.269       |
| Phosphorus  | 0.004       | 1.37      | 0.168      | 5.39              | 0.033       | 0.240       |
| Silicon     | 0.015       | 10.4      | 0.060      | 3.00              | 0.145       | 0.582       |
| Aluminium   | 0.013       | 1.25      | 0.029      | 0.807             | 0.054       | 0.160       |
| Magnesium   | 0.028       | 6.44      | 0.110      | 4.33              | 0.109       | 0.276       |
| Sodium      | -           | -         | -          | -                 | 0.051       | 0.092       |
| Zirconium   | -           | 0.015     | -          | 0.013             | -           | -           |
| Rubidium    | -           | 0.015     | -          | 0.013             | -           | -           |
| Plumbum     | 0.001       | -         | 0.001      | 0.006             | -           | -           |
| Oxygen      | 43.4        | 39.0      | 36.6       | 45.2              | 42.1        | 34.4        |
| Carbon      | 47.4        | 0.352     | 52.9       | 6.71              | 47.5        | 49.3        |
| Hydrogen    | 8.43        | -         | 8.34       | 0.34              | 8.048       | 7.760       |
| Nitrogen    | 0.570       | -         | 0.810      | -                 | 0.200       | 0.170       |

Ash and slag obtained by burning larch chips taken from under the combustion chamber have a heterogeneous grain size distribution (n = 0.644), while the focal residues are dominated by particles ranging in size from 250 to 2000 μm, the mass fraction of which is 53.26%.

Photographs of fly ash formed during the combustion of larch chips were obtained using the electronic scanning Zeiss SIGMA VP (Carl Zeiss) microscope. Microphotographs of fly ash were used to construct histograms of the distribution of microparticles and to determine the weight fractions (figure 3).

4. Discussion
Heat loss with flue gas is $q_2 = 6.6–7.7 \%$, but it rises when load and inlet boiler water temperature increases.

The values of the concentrations of carbon oxide corrected for an excess air coefficient of 1.4 are 12.0-139.2 mg/Nm$^3$.

Carbon loss when boiler operates on pellets was very low (0.22 %) due to the uniformity of the grain size distribution of the fuel, its low ash content, and a sufficiently high calorific value. Poplar chips have a higher ash content and a less uniform grain size distribution, which caused an increase in carbon loss, while the content of combustible substances in fly ash and slag was $C_{ash} = 41.69 \%$, $C_{slag}$
= 6.15%. Larch chips also have low ash content and low carbon losses (0.20%). The content of combustible substances in fly ash and slag was $C_{\text{ash}} = 53.6\%$, $C_{\text{slag}} = 7.06\%$.

Experimental studies have shown that the design of the boiler allows for efficient burning of both wood pellets and chips.

![Figure 3. Microparticles in flue gas when burning larch 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).](image)

To determine the external heat loss, an amended approach was used, based on a combination of relative and calorimetric methods supplemented with thermal imaging [4]. External heat loss does not exceed 0.5\% that is significantly lower in comparison with Russian standards [6-7].

Losses due to temperature of bottom ash while the boiler operates on larch chips did not exceed $q_6 = 0.01\%$ and poplar chips - $q_6 = 0.05\%$.

The gross boiler efficiency when working on larch chips 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 larch. When burning wood pellets the minimal emissions of nitrogen oxides and carbon monoxide were achieved.

Low NO$_x$ emission for each fuel is due to the moderate maximum temperatures and excess air in the combustion chamber, as well as two-stage combustion scheme. Sulfur dioxide in the combustion products was absent in all cases.

The results of studying the emission of soot particles using the external filtration method [8] under isokinetic conditions of gas extraction with the determination of the content of soot particles according to the method [9] showed that soot emission factor during combustion of larch chips was 11.81 g/GJ. The average PM2.5 emission factor (with a conversion coefficient of 0.14 [10]) was 1.653 g/GJ. The transition to the combustion of poplar chips was accompanied by a decrease in soot emission factor to 5.376 g/GJ and, accordingly, the PM2.5 emission factor to 0.753 g/GJ. When the boiler operates on pellets soot emission factor were 1.74 g/GJ (with a heating capacity of 72 KW). The PM2.5 emission factor was 0.243 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.

An analysis of the data (Figure 3) 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 100 μm. Particles with a size of 30 to 40 μm prevail when burning larch chips in the flue gas in a quantitative ratio, and the largest weight content falls on particles with a size more than 80 μm. 76.5% of particles in fly ash have a shape close to regular (ratio of length to equivalent diameter is ~ 1).
5. Conclusion
The analysis of fuels showed that as dry and ash free low calorific value as dry low calorific value of larch chips not inferior to spruce wood pellets. The low calorific value for dry and ash free weight of poplar and its bark is close to the values obtained for spruce, however, in terms of the low calorific value for dry weight, poplar and its bark is inferior due to the higher ash content.

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 larch and poplar chips, wood pellets. Within this framework, wood of larch and poplar should acquire worthy economic and industrial importance as an effective biofuel.

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