Combustion of wood pellets with a high amount of fines

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Abstract. A comprehensive study of the efficiency of the 1.5 MW Arimax Bio Energy hot water boiler operating on wood pellets with a high amount of fines has been carried out. Fuel characteristics and its compliance with the quality requirements of Russian and European standards have been investigated. The components of the heat balance and emission of harmful substances have been determined. Thermovision study of the boiler was carried out. The comprehensive study showed that the boiler provides sufficiently high technical and economic performance and minimal emissions of nitrogen oxides and carbon monoxide. However, the high amount of fines in the pellets significantly increases the emissions of particulate matter and especially black carbon into the environment.

1. Introduction
The vital activity of mankind is accompanied by the formation of a large amount of waste, the volumes of which are growing rapidly and pose a serious threat to our time. Waste from the harvesting and processing of wood due to high moisture content, low energy density and extremely heterogeneous particle size distribution are classified as difficult-firing fuels [1-3]. A promising direction for upgrading these wastes is their granulation, which makes it possible to increase their specific calorific value by 2.5–3.5 times, improve their logistics by 3–4 times, and reduce by 6–10 times the cost of biomass transportation, while further improving the manufacturability of all operations. This direction has been intensively developing in Russia since the beginning of the XXI century. The energy potential of this direction in the field of bioenergy, as in the case of fossil hydrocarbons, surpasses those of any country in the world [4-6].

An effective direction for a comprehensive solution to energy and environmental problems while meeting heating needs is the use of modern automated heat-generating plants operating on biofuels. Therefore, a series of modern automated boiler houses operating on wood pellets was installed in the Arkhangelsk region.

Studies of the efficiency of combustion of wood pellets were carried out on an Arimax Bio Energy hot water boiler in one of these boiler houses.

2. Description of hot water boiler
The Arimax Bio Energy hot water boiler has two circuits, deaerated water circulates in the first circuit. The design mode for the power fluid of the primary circuit is 110/90 °C. The heating of the secondary
circuit water (70/90 °C) takes place in a plate heat exchanger. The working pressure of hot water at the outlet of the boiler should not exceed 0.4 MPa, and the temperature should not exceed 115 °C.

The boiler screw feeder (Fig. 1) has a fuel re-ignition protection system, which is equipped with a fire detector and a sprinkler unit that is triggered when the screw surface temperature rises above 60 °C. The boiler feeder feeds the pellets to the profiled area of the furnace, where primary air passes through the gaps of the grate bars made of high-temperature cast iron with the addition of chromium, penetrating the fuel layer.

![Figure 1. Arimax Bio Energy boiler layout: 1 – service fuel hopper; 2 – secondary air fan; 3 – boiler; 4 – hot water line to heat exchanger; 5 – chimney; 6 – circulating pump; 7 – gas duct; 8 – flue-gas fan; 9 – multicyclone; 10 – furnace; 11 – primary air fan; 12 – fire-fighting system; 13 – fuel feeder.](image)

Secondary air is supplied to the above-layer zone of the furnace through nozzles with an inner diameter of 20 mm to ensure the afterburning of the combustible fuel components.

Combustion products provide heating of the boiler water of the primary circuit, making three pass in the fire tubes of the boiler, after which they are cleaned in a multicyclone (Fig. 1). The ash separated in the gas path is removed manually through the hatches located on the side walls of the boiler. The 1.5 MW Arimax Bio Energy multicyclone consists of nine elements. Particles of the caught ash are collected in a collecting hopper, which is tightly fixed to the outlet of the multicyclone. Combustion products by a flue-gas fan (with a 5.6 kW motor) are directed into a steel chimney with a diameter of Ø 325 × 8 mm and a height of \(h_{ch} = 10.5\) m. Each boiler is equipped with an individual chimney. To ensure smooth regulation of the boilers performance, the motor of flue-gas fans, screws, fans of primary and secondary air has frequency control. The minimum heating capacity of hot water boilers Arimax Bio Energy is 20% of the nominal.

Arimax Bio Energy boilers are equipped with the necessary safety devices to protect them from boiling of the power fluid, and safety valves (Prescor) set to a pressure of 0.4 MPa. The automation control system, made on the basis of Siemens elements, provides: the required fuel-air ratio, the specified vacuum level in the furnace and the oxygen concentration in the combustion products, maintaining the temperature of the outlet water in accordance with the set temperature. The
automation system is equipped with an Ethernet module and GSM modem, it provides the ability to remotely control the operation of the boiler room with a PC and a mobile phone, as well as controlling it through an Ethernet module using a PC.

The boiler is equipped with an individual control panel with automatic safety devices and automatic controls, performed on the basis of Siemens S7 200 microprocessors. Wall diagram is located on the outside of the control panel, showing the operation of the devices and is the center of the alarm.

Air intake fans of primary and secondary air to ensure the combustion process is carried out from the boiler room.

There is no possibility of controlling the resistance of the ash collector on the boiler, which does not allow an aerodynamic assessment of its degree of contamination. Monitoring the combustion process is carried out through the hatches located on the side walls of the boiler.

3. Materials and Methods
A series of tests with various modes of operation of the Arimax Bio Energy boiler was carried out during the energy study, when burning wood granules of the Sawmill 25.

Balance experiments were carried out in accordance with the requirements for production and operational testing of the second category of complexity [7].

Testo 350 XL gas analyzer was used in the study of the composition of combustion products. The pneumometric tube and Comark digital micromanometer were used to determine the flow of flue gases. The determination of velocity fields and flue gas flows was performed with a Pitot tube and micromanometer of Testo-435 precision instrument.

The external filtration method was used to determine the particulate matter concentration of the flue gases emitted into the atmosphere [7,8], while the filter holder of AFA was used to select the flow from gas ducts. The selection of dusting flow was carried out under conditions close to isokinetic. OP-442 TC impactor was used to measure and control the flow rate of selected combustion products. The calculation of the concentrations of the particulate matter in the flue gases and weight were carried out in accordance with the requirements [8].

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 mechanical durability of wood pellets was determined in accordance with the standard EN 15210-1 using the NHP portable Tester 100 of the German company Holman (lignotester).

The study of the grain size distribution of fuel and focal residues was carried out using AS 200 Control and "029" analyzers [7].

The temperature of the outer surfaces of the main and auxiliary equipment of the boiler was determined using a pyrometer and the results of thermovision.

Processing of experimental data was carried out using a multi-module software and methodological complex [9].

4. Results
The main research results are given in Table. 1. The main research results are given in Table. 1. Wood pellets of Sawmill 25, having a fairly homogeneous particle size distribution, were fed to the combustion chamber of the boiler when carrying out balance experiments. The values of the main thermal characteristics of the pellets: moisture content as received basis $W_{tr}=6.62 \%$; ash content $A'=0.76 \%$; lower calorific value $Q_{r}=17.34$ MJ/kg. The mechanical durability of the pellets was 99.16%. It is necessary to note the increased ash content and the high amount of fines in the burning pellets. So the weights of the particles less than 3.15 mm was more than 4.5 %, which correspondively led to an increase in the bulk density of the fuel to 0.705 g/cm$^3$.

Thus, the burning pellets did not correspond to the class A1 on the ash content and the amount of fines, on the amount of fines they also did not correspond to the classes A2 and B. Pellets complied with the requirements of Russian and European standards for the remaining parameters.
Table 1. The main performance of the boiler.

| Value                                               | Symbol, dimension | No. 1     | No. 2     | No. 3     | No. 4     | No. 5     |
|-----------------------------------------------------|------------------|-----------|-----------|-----------|-----------|-----------|
| Heat capacity                                       | $Q$, kW          | 651.3     | 976.9     | 1067.6    | 1239.8    | 1304.9    |
| Outlet operating pressure of the water             | $P_{o.p.}$, MPa  | 0.21      | 0.21      | 0.22      | 0.23      | 0.23      |
| Inlet water temperature                             | $t_{i.w.}$, °C   | 96.7      | 95.1      | 92.8      | 92        | 91        |
| Outlet water temperature                            | $t_{o.w.}$, °C   | 104.5     | 106.7     | 108.8     | 108.9     | 109.0     |
| Air flow rate primary/secondary                     | $V_{p}/V_{sec.}$ | 392/682   | 568/988   | 504/877   | 577/1005  | 599/1042  |
| Furnace draft / before ash collector                | $S_{f}/S_{a.c.}$ | 47/135    | 60/145    | 53/200    | 58/210    | 54/250    |
| Draft loss                                          | $S_{d}$, Pa      | 130       | 85        | 147       | 152       | 196       |
| Flue gas temperature                                | $q_{fg}$, °C     | 148.1     | 175.5     | 194       | 196.5     | 206.9     |
| Excess air in flue gas                              | $q_{ex}$         | 1.58      | 1.54      | 1.27      | 1.26      | 1.24      |
| Heat loss: flue gas                                 | $q_{2}$, %       | 7.41      | 8.94      | 8.61      | 8.68      | 9.12      |
| incomplete combustion                               | $q_{3}$, %       | 0.07      | 0.03      | 0.02      | 0.01      | 0.01      |
| carbon                                              | $q_{4}$, %       | 0.95      | 0.95      | 0.95      | 0.95      | 0.95      |
| external                                            | $q_{5}$, %       | 5.99      | 3.99      | 3.65      | 3.15      | 2.99      |
| Gross efficiency of the boiler                      | $n_{gross}$, %   | 85.56     | 86.06     | 86.74     | 87.19     | 86.91     |
| Total fuel consumption                              | $B$, kg/h        | 157       | 235       | 254       | 294       | 310       |
| Emission of NO$_x$                                  | NO$_x$, mg/MJ    | 40        | 46        | 49        | 46        | 45        |
| Emission of CO                                      | CO, mg/MJ        | 71        | 35        | 31        | 15        | 14        |
| Particulate matter emission                         | PM, mg/MJ        | -         | -         | 60.1      | -         | -         |

Analysis of the state of the gas path of the hot water boiler showed that the boiler has a high aerodynamic density of the lining. Inleakage of cold air in the section of the gas duct ash collector – flue-gas fan does not exceed the standard value ($\Delta\alpha_{a.c+flue} < 0.05$). However, the aerodynamic density of the gas paths should be periodically monitored, especially the zone of connection of collecting tanks to multicyclones.

The results of the experimental studies carried out have shown that the Arimax Bio Energy boiler is capable of providing the rated load with normal thermal characteristics of wood pellets.

**Figure 2.** Changing the air velocity of the secondary air in the fan inlet.

**Figure 3.** Changing the air velocity of the primary air in the fan inlet.
Balance experiments were carried out in the range of boiler loads from 60 to 100% of the nominal, while the water temperature at the outlet from the boiler varied in the range of $t_{\text{w}} = 104.5 – 109.0 \, ^{\circ}\text{C}$.

During the energy study, the excess air ratio of the supplied air was 1.18–1.52; and the fraction of primary air (0.45–0.55) was less than the fraction of secondary air, which is quite reasonable for wood pellets.

The ratio of primary to secondary air was 0.37 / 0.64, respectively. The boiler provides a high combustion efficiency of carbon monoxide even at low values of the excess air ratio at the outlet from the furnace, and its operation at high values of the excess air ratio ($\alpha^* > 1.52$) is accompanied by an increase in carbon monoxide emissions ($K_{\text{CO}} \geq 176 \, \text{mg/Nm}^3$). Changes in the velocities of primary and secondary air in the fan inlet are shown in Figures 2, 3.

5. Discussion

Heat losses due to incomplete combustion of the fuel were $q_3 = 0.01–0.07 \, \%$. The boiler gross efficiency varied in the range 85.56–87.19 \%. The specific consumption of fuel for the production of 1 Gcal was 163.7–166.3 kg of reference fuel/Gcal.

The water temperature at the boiler inlet was 91.0–96.7 \, ^{\circ}\text{C} during the energy tests. The gas-water heat exchanger provided insufficiently deep cooling of the combustion products, which caused a decrease in the efficiency of the boiler.

The decrease in the boiler efficiency also caused a significant amount of fines in the fired fuel. For comparison, at another boiler house in the Arkhangelsk region, similar tests of Arimax Bio Energy boilers with a nominal capacity of 1.5 MW were carried out [10]. The boiler efficiency in this case reached 90.38\%, since wood pellets with a low amount of fines were burned in the boiler furnace.

During the tests of the boiler house, a significant discrepancy between the values of the indicating devices for vacuum in the furnace of the Arimax Bio Energy boiler and the values displayed on the control panels was revealed.

The draft loss of the boiler along the gas path depends on its load, operating modes and characteristics of the fuel. When the heat output of the boiler was changed in the range of 60–100\% of the nominal, its draft loss was 70–250 Pa. The draft loss of the multicyclone could not be determined due to the absence of fittings on the gas ducts after it.

The boiler is cleaned at least once a year, and the multicyclone - once a month. Critical parameter for cleaning heating surfaces is an increase in the flue gas temperature to values of 250 \, ^{\circ}\text{C} and above (at a nominal heat capacity).

To maintain the degree of gas purification in the multicyclone at a high level, it is necessary to control the density of connection of collecting hoppers to the ash collector, which will avoid secondary entrainment of fly ash and an increase in energy consumption for draft. The noted regularities take place during the combustion of pellets with a uniform grain size distribution and a small amount of particles. Violation of the normal technological process when pelleting wood raw materials, especially an increase in its moisture content above the permissible level, leads to a low quality of the pellets and their subsequent self-destruction. The supply of such pellets or pellets with a high amount of fines to the furnaces of Arimax Bio Energy boilers can significantly reduce the efficiency and reliability of their operation due to a significant increase of carbon loss. Based on this, the incoming quality control of the pellets should be organized.

Analysis of the thermal operation conditions of the Arimax Bio Energy boiler showed that the heat loss with flue gases was 7.41–9.12\%. At the same time, an increase in this loss is noted with an increase in heat load.

Carbon loss was $q_4 = 0.95\%$. The combusted fuel contained high amount of fines, which caused the removal of particles that did not have time to burn out in the furnace volume of the boiler, while the content of combustible components in the fly ash was $C_{\text{fa}} = 21.11 \, \%$. The content of combustible substances in the slag has increased significantly ($C_{\text{slag}} = 43.48 \, \%$).
Most of the boiler piping has high-quality thermal insulation. However, there are pipelines where there is no thermal insulation (Fig. 4), which contradicts the requirements of regulatory documents [11-13].

Figure 4. Boiler room thermograms.

The reduced overall parameters of the Arimax Bio Energy boiler and the satisfactory quality of the lining and heat-insulating materials made it possible to reduce external heat losses, which cannot be determined using the traditionally used method [14]. Based on this, the value of this loss was determined on the basis of the results of measurements of the temperature of the outer surface of the boiler casing using a pyrometer and thermovision taking into account the overall characteristics and the ambient temperature. The results of thermovision made it possible to identify areas of the enclosing structures where the temperature does not meet the requirements of the current standards (Fig. 5-8). The calculated values of external heat losses were \( q_s = 2.99-5.99 \% \), large values of these losses correspond to the boiler operation modes with reduced loads.

Figure 5. Thermograms of the front wall of the boiler.

Figure 6. Thermograms of the right side of the boiler.
Figure 7. Thermograms of the rear wall of the boiler.

Figure 8. Thermograms of the gas dust after the boiler.

The total fuel consumption for the specified range of heat loads was \( B = 157 \text{–} 310 \text{ kg/h} \). It should be noted that the panel meters for fuel consumption in the boiler room give underestimated values. The data on the consumption of wood pellets obtained from the boiler panel meters cannot be used for calculations. Objective data on fuel consumption can be obtained only on the basis of the inverse heat balance equation, taking into account the recommendations \([14,15]\).

Low values of nitrogen oxide emissions from 40 to 49 mg/MJ are explained by a moderate level of maximum temperatures, as well as a two-stage fuel combustion scheme.

Sulfur dioxide was absent in the flue gases.

The range of changes in carbon monoxide emissions during the balance tests was 14–71 mg/MJ. The results of the experiments have shown that the Arimax Bio Energy boiler provides efficient combustion of combustible fuel components at an oxygen concentration in the combustion products at the output of the boiler of 4.0–6.0 % (at standard boiler density).

Studies of the particulate matter have shown that the emissions of particles have increased values (60.1 mg/MJ), which is associated with a high amount of fines in the fuel. Accordingly, the measurements performed also showed increased values of soot particle emissions (12.69 mg/MJ), which is explained not only by the high amount of fines in the burned pellets, but also by the high content of combustible substances in the fly ash.

Studies of the grain size distribution of fly ash caught in the ash collector showed that it has a high degree of polydispersity \((n=0.740; \, b=0.0478)\) and belongs to finely dispersed materials (Fig. 9). The fly ash is dominated by fractions with a particle size of less than 250 microns, which account for more than 98%. The results indirectly suggest a high separation capacity of the ash collector.
Studies of the distribution of combustible substances by fractions in fly ash have shown that particles with a size of 125 microns and more have the maximum combustible content (Fig. 10). However, their mass fraction in fly ash is small. Therefore, the decisive influence on carbon loss with slag and fly ash is exerted by the content of combustible substances in particles less than 125 microns in size (Fig. 11).

**Figure 9.** Fly ash grain size distribution.

**Figure 10.** Fractional content of combustible substances in fly ash.

**Figure 11.** The content of combustible substances in fly ash, taking into account the mass fractions of various fractions.

6. Conclusion
The results of a comprehensive energy study showed that the Arimax Bio Energy boiler, operating on wood pellets, despite the previously mentioned drawbacks, has sufficiently high technical, economic and environmental performance, but there is significant potential for their further improvement.

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