Efficiency of burning sediments of waste water in a boiling layer

V K Lyubov ¹, A M Vladimirov ² and P V Koroleva ¹

¹ Northern (Arctic) federal University named after M.V. Lomonosov, Russia, 163002 Arkhangelsk, Severnaya Dvina emb., 17
² JSC Arkhangelsk Pulp and Paper Mill, Russia, 164900, Arkhangelsk Region, Novodvinsk, Melnikova, 1

vk.lubov@mail.ru

Abstract. It has been experimentally shown that the Metso HYBEX steam boiler installed at CHP-1 of JSC APPM and designed to burn a mixture of bark and wood waste and sewage sludge ensures their efficient utilization without highlighting fuel oil. At boiler loads close to the nominal efficiency, the gross value was 85.22–85.24%. The environmental indicators of the boiler unit fully and even with a margin meet the requirements established by directive 2010/75 / EC and GOST R 50831-95. The operation of the boiler ensured the complete utilization of sewage sludge generated at the sewage treatment plant. The annual savings of fossil fuels amounted to more than 80 thousand tons of fuel equivalent. The total content of heavy metals in fly ash emitted into the atmospheric air by a recycling and energy boiler with a bubbling fluidized bed when burning high-moisture biofuels is many times lower than when burning coal, even in low-emission furnaces.

1. Introduction

It is known from world practice that the main part of wastewater in settlements, pulp and paper, petrochemical and other industries is treated by biological methods using activated sludge. In this case, the traditional scheme is usually used, which includes the following basic operations: mechanical treatment of wastewater in primary sumps, biological treatment in aeration tanks, purification of suspended particles of activated sludge in secondary sumps, post-treatment of water and disinfection [1]. The main drawback of the classical scheme of biological treatment of wastewater is the formation of a large amount of spent sludge, as a result of the transformation of part of the initial pollution into active biomass. Disposal of sewage sludge (WWS) is a more time-consuming task than directly treating it; therefore, technologies to reduce the amount of this waste are economically viable and environmentally sound.

WWS is a complex organic-mineral complex, the organic part of which is biomass and adsorbed and partially oxidized pollutants of wastewater, as well as nitrogen and phosphorus compounds. The main components of the mineral part are silicon oxide, alumina, iron oxide and phosphorus, which may be in the form of poorly soluble phosphates of heavy metals, as well as calcium. There are a number of ways to dispose of WWS: dumping into the seas and oceans, burning, burial in soil, neutralization and use as organic fertilizers, as an additive in the preparation of various composts, etc. [1-3]. At present, in Russia, the main way to treat WWS is to mechanically dehydrate them and store them on silt maps and sludge collectors, where waste decontamination and biodegradation have been going on for a long time. This method does not meet modern environmental and technical requirements, leads to a long...
and most often to irrevocable alienation of significant land resources, is accompanied by significant risks of groundwater pollution in the influence zone of waste storage sites [4].

In many countries of the world, the combustion process is considered as one of the main alternative ways of disposing of waste characterized by high levels of organic substances. The main advantage of burning such waste is a significant reduction in its mass (by about 97%) and volume (up to 98%), which is especially important in conditions of a shortage of free space for the organization of landfills and landfills. When burning, many hazardous organic compounds decompose, and the use of generated heat to generate electricity and ash and slag residues for the production of some materials can partially offset the cost of waste disposal. Some experts believe that burning is almost the only real way to solve such an important environmental, sanitary and social problem as disposal of WWS [5]. Moreover, in most cases, these wastes are classified as biofuels having an extremely low energy value.

2. Energy use of by products of pulp and paper production

In the pulp and paper industry, biofuel uses waste generated during the preparation of wood raw materials and in the chemical processing of wood - bark, sawdust, spent liquor, WWS. The technology for burning liquid waste in the form of spent liquors in the furnaces of energy-technology boiler units is well established, and along with the generation of energy, chemicals are regenerated [6]. The bark and sawdust are used quite successfully for energy purposes [7]. The greatest problems arise with the energy utilization of WWS. To increase the energy value of WWS, their mechanical dehydration on filter presses at a pressure of 0.2–0.5 MPa is widely used [1, 3, 4, 8]. Recently, preference has been given to decanter centrifuges, which allow to obtain the relative humidity of the pressed sediment in the limit 70–79%. However, such humidity of the WWS allows it to be burned only in a mixture with fuel material having lower humidity.

In order to completely utilize the waste generated during the processing of wood biomass in the pulp and paper mill cycle, including the biological wastewater treatment sludge, in 2014 Metso HYBEX high-pressure steam boiler operating on a mixture of bark and wood wastes (BWW) and WWS was put into operation at JSC APPM. The energy use of sewage sludge at JSC APPM is caused by environmental considerations, since the daily formation of sludge is about 600 tons, which requires large areas for its disposal, which APPM does not have.

The HYBEX boiler unit with a bubble fluidized bed with one drum is equipped with a firebox with a gas-tight design of the membrane walls. The second and third stages of the superheater are located in the upper part of the furnace, which is the first vertical gas duct. The sections of the first stage of the horizontal type superheater are located in the second vertical gas duct. The smooth tube type economizer and air heaters are located in the third vertical gas duct. The boiler is equipped with one starting fuel oil burner and two working fuel oil burners. A mixture of bark and wood fuel and WWS is fed into the fluidized bed in a single stream from the front wall of the boiler. To clean flue gases from solid particles, the boiler is equipped with an electrostatic filter consisting of one chamber and two fields. The boiler unit produces high pressure steam (10 MPa), with a temperature of 540 °C; its nominal steam capacity is 83.5 t/h at a feed water temperature of 215 °C.

In the furnace chamber of the boiler, a three-stage fuel combustion scheme is implemented. At the same time, some of the recirculation gases taken after the main smoke exhaust of the boiler are introduced into the primary air flowing to the liquefaction of the fluidized bed. This allows you to adjust the temperature of the fluidized bed and, accordingly, the combustion process of the fuel mixture. Secondary and tertiary air are introduced as the torch rises using a separate fan, while the secondary nozzles are installed on the front and rear walls (8 + 8 pcs.), and the tertiary air on the right and left walls (5 + 5 pcs.) above secondary air nozzles. The primary and secondary air temperatures (Table 1) were in line with the recommended values. A separate fan is used to introduce primary air.
### Table 1. Results of the HYBEX Metso boiler №8 test JSC APPM.

| Value                                           | Dimension | Tests     |
|-------------------------------------------------|-----------|-----------|
| Steam production                                | t/h       | 69.8 70.5 |
| Superheated steam pressure                      | MPa       | 9.1 9.10  |
| Superheated Steam Temperature                   | °C        | 543 544  |
| Feed water temperature                          | °C        | 154 154  |
| Humidity BWW / WWS / mixture                    | %         | 54.56 / 78.70 / 63.25 |
| Ash content of BWW / WWS / mixture              | %         | 2.22 / 2.61 / 2.36 |
| Calorific value BWW / WWS / mixture             | MJ/kg     | 7.33 / 2.10 / 5.45 |
| Primary air temperature                         | °C        | 196 198  |
| Secondary air temperature                       | °C        | 203 203  |
| Fluidized bed temperature                       | °C        | 818 821  |
| The proportion of air going to the fluidized bed | %         | 48.5 47.7 |
| Gas temperature before / after the primary      | °C        | 555 / 448 559 / 452 |
| superheater                                     |           |           |
| Gas temperature before / after air heater       | °C        | 233 / 175 236 / 177 |
| Depression in the furnace                       | Pa        | 250 230  |
| Vacuum before / after electrostatic precipitator| kPa       | 2.34 / 2.66 2.35 / 2.67 |
| Excess air after air heater                     |           | 1.53 1.54 |
| Heat loss:                                      |           |           |
| flue gas                                        | %         | 13.35 13.35 |
| incomplete combustion                            | %         | 0.01 0.01 |
| carbon                                          | %         | 0.48 0.47 |
| external                                        | %         | 0.77 0.76 |
| sensible heat of slag                           | %         | 0.17 0.17 |
| Gross efficiency of the boiler                  | %         | 85.22 85.24 |
| Total fuel consumption                          | t/h       | 43.127 43.589 |
| Emission of CO                                  | mg/MJ     | 8 9 |
| Emission of NOx                                 | mg/MJ     | 108 103 |
| Emission of SO₂                                 | mg/MJ     | 58 63 |
| Particulate matter emission                     | mg/MJ     | 1.13 1.07 |
| Emission of HCl                                 | mg/MJ     | 3.95 3.77 |

### 3. Experimental methods

In the process of industrial and operational tests of the boiler, sampling of fuel, quartz sand, furnace ash, as well as ash and slag was carried out in accordance with [9]. After preliminary preparation and reduction, the particle size distribution of the fuel mixture, inert filling, furnace and fly ash was studied using the sieve method and Retzsch AS 200 Control analyzer in accordance with the requirements of GOST 2093-82. For each fraction of fly ash extracted during the sieve analysis, the content of combustible substances was determined in accordance with the requirements of GOST 11022-95 and microscopic studies were carried out using a Zeiss SIGMA VP scanning electron microscope to determine their structure, size, shape and quantitative composition.

To determine the elemental composition of different fractions of pre-dried fly ash, an X-ray fluorescence EDX-8000 spectrometer was used. The principle of operation of the spectrometer is based on measuring the intensity of the fluorescent radiation emitted by the atoms of the determined elements contained in the test sample under the influence of x-rays. The radiation intensity is proportional to the content of the corresponding element. Moreover, each element that is part of the sample fluoresces at a specific wavelength. The device allows you to simultaneously detect, measure and record the radiation intensity of various elements.
The determination of the composition of the combustion products was carried out using stationary systems for monitoring the emissions of harmful substances, which are equipped with the Metso HYBEX boiler unit.

The thermal characteristics of the fuel mixture and its components were determined in accordance with GOST R 54186-2010, GOST R 54211-2010, GOST R 54185-2010 and GOST R 54184-2010. The specific calorific value was measured using an IKA C 2000 Basic Version 2 calorimetric bomb with a LOIP FT-216-25 liquid cryothermostat in accordance with GOST 147-95.

The entire processing of experimental data on the operation of the boiler unit was carried out using a multi-module program-methodological complex [7], while the gross efficiency was determined by the equation of the inverse balance.

4. Results and Discussions

A study of the efficiency of the boiler unit at a load of 0.91–0.92 of the nominal was carried out when burning a mixture of BWW and WWS, while the mass fraction of the latter was 0.36. The combustible fuel mixture had a high degree of heterogeneity of the particle size distribution (average polydispersity coefficient $n = 0.969$, and the coefficient characterizing the composition fineness $b = 9.19 \cdot 10^{-5}$).

The granulometric composition of quartz sand supplied to the furnace was rather uniform (Fig. 1). The mass fraction of particles with a size of $1.0 < x < 2.0$ mm was 0.85. The thermal characteristics for the working mass of the individual components and the fuel mixture as a whole are given in Table 1. Despite the extremely unfavorable thermal characteristics of the fuel mixture, the boiler unit worked stably without fuel oil. The temperature of the “fluidized bed” was $818–821 ^\circ$ C, and the proportion of air going to its “liquefaction” was 47.7–48.5%. This mode of combustion ensured the complete oxidation of foul-smelling gases and the efficient burning of combustible components of the fuel.

![Figure 1](image1.png)

**Figure 1.** Integral grain characteristic: a) 1 - wood waste and WWS; 2 - quartz sand; 3 - furnace ash returned to the furnace; b) 1 - ash from the electrostatic precipitator; 2 - ash from under the 3rd gas duct; 3 - ash from under the 2nd gas duct; 4 - rejected furnace ash

The content of combustible substances in fly ash trapped in the electrostatic precipitator was 1.7–1.9%. A study of the granulometric composition of fly ash and the fractional content of combustible substances showed that the burning of combustible components in particles with a size of $63 < x < 125$ $\mu$m has a decisive effect on heat loss with mechanical incomplete combustion (Fig. 2b). The presence of three vertical flues in the boiler unit causes the appearance of turns of the gas stream, during which an inertial-gravitational separation of solid particles occurs. The selection and particle size analysis of the separated solid phase showed that the result of these processes is to increase the uniformity of the solid phase. The values of the polydispersity coefficient in this case changed as follows: $n = 0.673$ - after the second vertical gas duct; $0.764$ - after the third and $1.254$ - ash from the hoppers of the electrostatic precipitator.
Figure 2. The content of combustible substances in fly ash trapped in the electrostatic precipitator: a - the fractional content of combustible substances; b - fuel content, taking into account the mass fractions of various fractions.

To ensure efficient operation of the fluidized bed, the spent material of the layer is removed from different zones of the bottom of the furnace through four funnels and trays, and transported using a scraper chain conveyor with water cooling to the screening device of the furnace ash, in which it is divided into material suitable for return to the furnace \((x < 1.6 \text{ mm})\), and coarse material \((x > 1.6 \text{ mm})\), which is discharged using a scraper conveyor into a container of rejected furnace ash. The results of the analyzes showed that most of the rejected furnace ash (Fig. 1) can be reused to compensate for the loss of “fresh” silica sand, which will help reduce operating costs. A quantitative assessment of the rejected material removed from the fluidized bed and “fresh” fed to the fluidized bed is carried out by changing the pressure of the primary air under the layer, based on the following ratio of 0.1 kPa to 0.5 t of the layer material.

When performing an energy survey, the water temperature at the inlet to the economizer of the boiler unit had lower values (Table 1), which necessitated the calculation of the reduced steam capacity [7] to improve the accuracy of calculating heat loss to the environment. The total resistance of the gas path of the boiler in the studied load range had elevated values of 2.41–2.44 kPa, which is primarily associated with high humidity of the combusted fuel. The performed studies showed that the boiler unit provides efficient combustion of the fuel mixture with extremely unfavorable thermal characteristics, while the gross efficiency was 85.22–85.24%.

The elemental composition of different fractions of fly ash was determined using an EDX-8000 X-ray fluorescence spectrometer. During the experiments, the content of 22 elements was determined, however, in accordance with the objectives, Table 2 shows the contents of only some heavy metals. To conduct a comparative analysis, the content of heavy metals in the fly ash of a boiler with fluidized bed was adjusted taking into account the differences in the content of combustible substances in different fractions of ash. Based on the results obtained, it is seen that the content of heavy metals in fly ash increases with decreasing particle size. This fact is associated with an increase in the external specific surface of small particles. Based on this, it should be expected that fine ash not trapped in the electrostatic precipitator of this boiler unit contains more toxic trace elements than the average ash composition of the initial fuel mixture [10, 11].

Based on the results of the study of the content of heavy metals in various fractions of fly ash, their emissions into the atmospheric air with particles not captured in the electrostatic precipitator of the HYBEX boiler unit were calculated (Table 3). When performing the calculations, we used data on the content of heavy metals for particles less than 45 μm, the gross efficiency of the boiler, obtained by the reverse balance equation at a load close to the nominal and mass fraction of WWS equal to 0.36, as well as the results of stationary monitoring of the concentration of solid particles in front of the chimney.
TABLE 2. Heavy metals amount in various fractions of fly ash, %.

| Item       | Particle size, μm | 0  | 1  | 2  | 3  | 4  | 5  |
|------------|-------------------|----|----|----|----|----|----|
|            | x < 45            | 45 | 63 | 125| 250| Gross sample |
| Ba         | 0.179             | 0.128 | 0.086 | 0.071 | 0.049 | 0.0958 |
| Zinc       | 0.330             | 0.200 | 0.116 | 0.102 | 0.095 | 0.143 |
| Copper     | 0.017             | 0.015 | 0.010 | 0.008 | 0.006 | 0.0107 |
| Zirconium  | 0.445             | 0.266 | 0.222 | 0.071 | 0.026 | 0.2052 |
| Iron       | 3.690             | 3.370 | 2.320 | 1.902 | 1.86 | 2.461 |
| Manganese  | 1.180             | 0.941 | 0.534 | 0.299 | 0.176 | 0.578 |
| Chromium   | 0.068             | 0.059 | 0.044 | 0.043 | 0.022 | 0.0478 |

The specific emissions of heavy metals with small particles of ash not captured by the ash collector and attributed to 1 kWh of energy generated for a recovery and energy boiler with a fluidized bed were much lower than when burning a mixture of Intinsky and Kuznetsk coal, even when using VIR-technology [10]. This is primarily due to the higher content of heavy metals in the fly ash of coal-fired boilers and significantly higher ash content of combusted fuel.

TABLE 3. Estimated grade of heavy metals in fly ash, mg/kWh.

| Item | Ba | Zn | Cu | Zr | Fe | Mn | Cr |
|------|----|----|----|----|----|----|----|
|      | 0.00791 | 0.0146 | 0.000751 | 0.0197 | 0.163 | 0.0522 | 0.00301 |

Stationary systems for controlling emissions of harmful substances are installed in the gas path of boiler No. 8 of CHP-1 of JSC APPM. Emissions of pollutants emitted into the air had the following values: NOx = 103–108; CO = 8–9; SO2 = 58–63; solid particles 1.07–1.13; HCl = 3.77–3.95 mg / MJ. The emission of soot particles was 0.0193–0.0203 mg / MJ.

5. Conclusions

The results of the studies showed that the Metso HYBEX steam boiler, designed to burn a mixture of bark and wood waste and sewage sludge, ensures their efficient utilization without highlighting fuel oil, even with an increase in the relative humidity of the mixture to 63.3%. With a boiler load of 0.91–0.92 of the nominal gross efficiency, it was 85.22–85.24%. Heat losses with mechanical incomplete combustion of the fuel did not exceed 0.5%, while the decisive influence on the value of this loss was exerted by the incomplete burning of combustible components in particles with a size of 63 < x < 125 μm. The environmental indicators of boiler unit No. 8 fully, and even with a large margin, comply with the requirements established by directive 2010/75 / EC and GOST R 50831-95.

The commissioning of the HYBEX boiler unit at CHP-1 of the JSC APPM made it possible to ensure complete utilization of WWS generated at treatment facilities and the production of high-pressure steam going to the combined production of heat and electric energy. The annual savings of fossil fuels amounted to more than 80 thousand tons of fuel equivalent.

The determination of the content of heavy metals in various fractions of fly ash, performed using an X-ray fluorescence spectrometer, showed that the total content of heavy metals in fly ash emitted into the atmosphere by a boiling fluid-energy boiler when burning high-moisture biofuels is many times smaller than when burning coal, even in low-emission furnaces.

Acknowledgments

The authors are grateful to the staff of the Center for the Protection of Arctic for carrying out research on an X-ray fluorescence spectrometer and an electronic scanning microscope.

References.
[1] Voronov Yu V and Yakovlev S V 2006 *Water Disposal and Wastewater Treatment* (Moscow: Association of Construction Universities Press) p 704

[2] Pakhnenko E P 2007 *Sewage Sludge and Other Non-traditional Organic Fertilizers* (Moscow: BINOM Press) p 311

[3] Sobgayda N A and Solodkova A B 2015 *International Journal of Environmental Problems*, vol 1, Is. 1 pp 64—74

[4] Gulyaeva I S, Dyakov M S and Savinova Ya N 2012 *Bulletin of the Perm National Research Poly-Technical University. Environmental Protection, Transport and Life Safety*, vol 2 pp 18—32

[5] Yanin E P 2006 *Resource-Saving Technologies*, vol 24, pp 3—29

[6] Zhuchkov P A, Goflin A P and Saunin V I 1991 *Heat Pulp and Paper Production* (Moscow: Ekologiya Press) p 350

[7] Lyubov V K and Lyubova S V 2017 *Increasing of Biofuels Usage Efficiency* (Arkhangelsk: Northern (Arctic) federal University Press) p 533

[8] Zhuchkov P A 1978 *Thermal Processes in Pulp and Paper Production* (Moscow: Forest Industry Press) p 407

[9] Trembovlya V I, Finger E D and Avdeeva A A 1961 *Heat Engineering Tests of Boiler Installations* (Moscow: Energoatomizdat Press) p 416

[10] Lyubov V K and Finker F Z 2020 *AIP Conf. Proceedings* 2211, 040002

[11] Krylov D A 2012 *Powerman* № 11, pp 36—39