Sewage Sludge Utilization for Power Production

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Abstract. It has been experimentally shown that the Metso Hybex steam boiler, installed at CHP-plant No.1 of AO APPM and designed to burn a mixture of bark and wood waste and sewage sludge, ensures their efficient utilization without fuel oil support flaming. The gross efficiency was 85.22–85.24% at boiler unit loads close to the nominal. The environmental performance of the boiler fully complies with the requirements established by directive 2010/75/EU and GOST 50831-95. The operation of the boiler ensured the complete utilization of sewage sludge generated at the water and wastewater treatment facility. The annual savings of fossil fuels amounted to more than 80 thousand tons of reference fuel. The total content of heavy metals emitted into the atmosphere with fly ash by a Hybex boiler with a bubbling fluidized bed when burning high-moisture biofuels is many times lower than when burning coal.

1. Introduction
The main part of sewage from settlements, pulp and paper, petrochemical and other industries is treated by biological methods using sludge. In this case, a traditional scheme is usually used, which includes the following operations: primary mechanical wastewater treatment, biological purification in aerotanks, purification of suspended particles of sludge in secondary clarifiers, water after purification and disinfection [1]. The main drawback of the classical scheme of biological wastewater treatment is the formation of a large amount of waste activated sludge, as a result of the transformation of part of the initial pollution into active biomass.

There are a number of methods for disposal of sewage sludge (SS), discussed in detail in [1-11]. Currently, the main method of SS treatment in Russia is their mechanical dehydration and storage on sludge lagoons and sludge collectors, where waste disinfection 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 [12].

In many countries, the combustion process is considered as one of the main ways of disposing of waste characterized by high levels of organic substances. This method can significantly reduce the mass and volume of waste, which is especially important in conditions of a shortage of free space for the organization of landfills. Many hazardous organic compounds decompose when burned, and the use of heat to generate electricity and ash and slag to produce some materials may partially offset the cost of waste disposal. Some experts believe that burning is almost the only way to solve such an important sanitary, environmental and social problem as disposal of SS [13]. These wastes are classified as biofuels with extremely low calorific value.
2. Energy use of by-products of pulp and paper production

The pulp and paper industry use waste generated during the preparation of wood raw materials and in the chemical processing of wood (bark, sawdust, spent liquor, SS). At the same time, technologies for burning spent liquors in the furnaces of industrial power boilers are well developed, and along with the generation of energy, chemicals are regenerated [14]. The bark and sawdust are used quite successfully for energy purposes [15]. The biggest problems arise with the energy utilization of SS. In order to increase the calorific value of SS, its dehydration is widely used [1, 3, 12, 16]. At the same time, decanter centrifuges have recently been preferred, which make it possible to obtain the relative moisture of the pressed settled sludge in the range of 70–79%. However, such moisture of the SS allows it to be burned only in a mixture with fuel material having lower moisture.

In 2014, Metso Hybex boiler operating on a mixture of bark and wood waste (BWW) and SS, for the complete utilization of waste generated during the processing of wood biomass in the pulp and paper mill cycle was commissioned at Arkhangelsk Pulp and Paper Mill (APPM). The energy use of SS is caused by environmental considerations, since the daily formation of settled sludge is about 600 tons, which requires large areas for its placement, which APPM does not have.

The Hybex boiler with a bubble fluidized bed has one drum and is equipped with a furnace with a gas-tight membrane wall design. 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 plain-tube economizer and air heaters are located in the third vertical gas duct. The boiler is equipped with one starting oil burner and two load oil burners. The boiler is equipped with an electrostatic filter for cleaning flue gases from particulate matter. 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.

A three-stage fuel combustion scheme is implemented in the furnace chamber of the boiler. The primary air flowing to liquefy the "fluidized bed" is introduced as part of the recirculation gases taken after the main boiler exhaust fan. This allows to adjust the temperature of the "fluidized bed" and the combustion process. Secondary and tertiary air are introduced as the torch rises using a separate fan. The primary and secondary air temperatures (Table 1) were in line with the recommended values. A separate fan is used to introduce primary air. Forced-draft installations are equipped with frequency controllers.

3. Experimental methods

In the process of industrial and operational tests of the boiler, sampling of fuel, silica sand, furnace ash and slag was carried out in accordance with the [17]. After preliminary preparation and quartation, their particle size distribution was studied using the sieve method and Retzsch AS 200 Control analyzer. For each fraction of fly ash extracted during the sieve analysis, the content of combustible substances was determined, and microscopic studies were performed using a Zeiss SIGMA VP scanning electron microscope to determine their structure, size, shape and quantitative distribution.

An X-ray fluorescence spectrometer EDX-8000 was used to determine the elemental composition of different fractions of pre-dried fly ash. The device allows you to simultaneously detect, measure and record the radiation intensity of various elements. It was also used to determine the elemental composition of SS and the ash formed during its combustion.

The composition of the combustion products and the content of their solid fraction were determined, using stationary systems for controlling emissions of harmful substances.

The burning characteristics of the fuel mixture and its components were determined by standard methods [17]. The calorific value was measured using an IKA C 2000 Basic Version 2 calorimetric bomb with a cryothermostat.

The entire processing of experimental data on the study of the operation of the boiler was carried out using a program-methodical complex [15, 21], while the gross efficiency was determined by the equation of indirect heat 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 while burning a mixture of BWW and SS, while the mass fraction of the latter was 0.36. The fuel mixture had a high degree of heterogeneity of particle size distribution (average polydispersity coefficient $n = 0.969$, and the coefficient characterizing the fineness of the composition $b = 9.19 \cdot 10^{-5}$). The particle size distribution of silica sand fed into the fluidized bed was quite uniform ($n = 3.30$, $b = 8.22 \cdot 10^{-12}$). The mass fraction of particles with a size of $1.0 < x < 2.0$ mm was 0.85. Burning characteristics as received of the separate components and the fuel mixture are given in Table 1. Despite the extremely unfavorable burning characteristics of the fuel mixture, the boiler worked stably without fuel oil support flaming. The temperature of the "fluidized bed" was 818–821 °C. This mode of combustion ensured the complete oxidation of non-condensable gases and the efficient burning of combustible components of the fuel. The content of combustible substances in fly ash trapped in the electrostatic filter was 1.7–1.9%. The study of the particle size distribution of fly ash and the fractional content of combustible substances showed that the burning of combustible components in particles with a size of $63 < x < 125$ μm has a decisive effect on carbon loss. The presence of three vertical ducts in the boiler causes the appearance of turns of the gas stream, during which an inertial-gravitational separation of particles occurs. Sampling and particle size analysis of particulate matter 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 duct and 1.254 - ash from the hoppers of the electrostatic filter.

To ensure an effective “fluidized bed”, the spent material of the bed is removed from different zones of the furnace bottom through four hoppers and trays, and transported using a water-cooled scraper conveyor to the screening devices of the bottom ash, in which it is separated into material suitable for return to a furnace ($x < 1.6$ mm), and coarse material ($x > 1.6$ mm), which is discharged by conveyor into the container. Studies have shown that most of the rejected bottom ash can be reused to compensate for the loss of “fresh” silica sand, which will help reduce operating costs.

The water temperature at the inlet to the economizer of the boiler had lower values (Table 1), which necessitated the calculation of reduced steam capacity according to the method [7] to increase the accuracy of calculating external heat loss. The total resistance of the gas path of the boiler in the studied load range had higher values (Table 1), which is associated with high moisture of the combusted fuel. The performed studies showed that the boiler unit provides efficient combustion of the fuel mixture with extremely unfavorable burning characteristics, while the gross efficiency was 85.22–85.24%.

In the course of experiments performed using an EDX-8000 X-ray fluorescence spectrometer, the content of 22 elements was determined, however, in accordance with the tasks set, the contents of only some heavy metals are given in Table 2, 3. It should be noted that with SS ashing, the mass content of heavy metals increases, while the degree of their concentration varied in the range of 1.62–3.84 times (Table 2).

**Table 2.** The content of heavy metals in the dry SS and in its ash, %.

| Content  | Ba  | Zn  | Cu  | Zr  | Fe  | Mn  | Cr |
|----------|-----|-----|-----|-----|-----|-----|----|
| SS       | 0.044 | 0.074 | 0.009 | 0.030 | 1.750 | 0.323 | 0.019 |
| SS ash   | 0.153 | 0.120 | 0.028 | 0.109 | 5.780 | 1.110 | 0.073 |

To conduct a comparative analysis, the content of heavy metals in the fly ash of the boiler is adjusted taking into account the content of combustible substances in various fractions of the 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 specific outer surface of small particles. Based on this, it should be expected that fine ash, not trapped in the electrostatic filter of this boiler, contains more toxic air pollutants than the average ash composition of the initial fuel mixture [18–20].

**Table 3.** Heavy metals amount in various fractions of fly ash, %.

| Item         | Particle size, μm | Gross sample |
|--------------|-------------------|--------------|
| Content      | $x < 45$ | $45 \leq x < 63$ | $63 \leq x < 125$ | $125 \leq x < 250$ | $250 \leq x$ | Gross sample |
| Barium       | 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 |

Based on the results of a study of the heavy metals content in various fractions of fly ash, their release into the atmosphere with particles not captured in the electrostatic filter of the Hybex boiler were calculated (Table 4). 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 indirect heat balance equation, at a load close to the nominal and mass fraction of SS equal to 0.36, as well as the
results of stationary monitoring of the concentration of particulate matter in front of the chimney. Studies performed using an electron scanning microscope for the finest fraction of fly ash (x<45 μm) trapped in an electrostatic filter showed that particles smaller than 10 μm prevail quantitatively. However, the highest weight content falls on particles 20<x<40 μm (Fig. 2 a). More than 70% of the particles have a shape close to regular or the ratio of length to equivalent diameter is ~ 1 (Fig. 2 b).

**Figure 1.** The structure of particulate matter formed during the combustion of a mixture of BWW and SS.

**Figure 2.** Microparticles in flue gas when burning mixture of BWW and SS: a – quantity distribution and weight content of particles with different sizes; b – quantity distribution of particles by shape (ratio of length to equivalent diameter).

The total emissions of heavy metals with small particles of ash not captured by the ash collector and attributed to 1 kWh of generated energy for the Hybex utilization and energy boiler were much lower than when burning coal in boilers with VIR technology [18]. 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 the combusted fuel.

**Table 4.** Estimated grade of heavy metals in fly ash, mg/kWh.

|     | Ba     | Zn     | Cu     | Zr     | Fe     | Mn     | Cr     |
|-----|--------|--------|--------|--------|--------|--------|--------|
|     | 0.00791| 0.0146 | 0.000751| 0.0197 | 0.1630 | 0.0522 | 0.00301|

Stationary systems for controlling emissions of harmful substances are installed in the gas path of boiler No. 8 of CHP-plant No.1 of APPM. The performed studies showed that the boiler provides efficient combustion of the fuel mixture with extremely unfavorable burning characteristics, while
ensuring good environmental performance (Table 1). 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 BWW and SS, ensures their efficient utilization, even when the relative moisture of the mixture increases to 79%. The gross efficiency was 85.22–85.24% at a boiler unit load of 0.91–0.92 of the nominal. The environmental performance of the boiler fully complies with the established requirements.

The commissioning of the Hybex boiler at CHP-plant No.1 of APPM made it possible to ensure complete utilization of SS generated at the water and wastewater treatment facility 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 reference fuel.

Determination of the content of heavy metals in various fractions of fly ash showed that the total content of heavy metals in fly ash emitted into the atmosphere by the Hybex boiler when burning high-moisture biofuels is many times lower than when burning coal in low-emission furnaces.

6. References
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