

OIL SHALE PULVERIZED FIRING: BOILER EFFICIENCY, ASH BALANCE AND FLUE GAS COMPOSITION

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Abstract. *The paper presents analyses of data obtained from oil shale pulverized firing tests carried out at the Eesti Power Plant (EPP) that is part of an Estonian power company Narva Power Plants (NPP) owned by a state company Eesti Energia AS. The tests were conducted at two boiler loads: 50% (158 t/h) and 100% (320 t/h) in the TP-101 boiler. During experiments samples of bottom and fly ashes from inertia dust collectors after the super heater (SH) and economizer (ECO), as well as fly ash from the electrostatic precipitator (ESP) of the first, second and third fields were taken. Analysis of the gas sample taken at the ESP exit was performed. The ash distribution at different ash discharge ports was obtained. Analysis of the ash chemical composition was carried out. The specific consumption of oil shale per useful heat and gross electricity production was found and other techno-economic characteristics were determined. The tests at partial and nominal loads showed that the emission of SO₂, CO₂, CO, NO and HCl at nominal load were essentially higher. The content of fine ash particles (<2.5 µm) after the ESP was higher at nominal load.*

Results of analysis can serve as a basis for future research and development projects. Also, they can be used to decide whether to continue operation of PF units.

Keywords: *oil shale, pulverized firing, boiler efficiency, ash balance, flue gas composition.*

1. Introduction

Eesti Energia AS is Estonia's leading and one of the most significant power generating companies in the Baltic region. The company owns two power plants in the vicinity of Narva city – the Balti Power Plant (BPP) and the Eesti Power Plant (EPP), which are the biggest oil shale fired power plants

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in the world [1]. Most of power plants units are based on pulverized firing (PF) technology which has been applied since the 1960s. In the year 2004 the circulating fluidized bed (CFB) technology was successfully implemented for oil shale combustion. Since then a lot of studies have been conducted to describe this technology and determine the positive and negative aspects regarding oil shale combustion. Some of the results concerning the CFB technology and boiler reliability are presented in [2–15]. Even though CFB is the best available technology, the use of the PF technology is still needed to meet the energy demand during the period of transition from PF to CFB. At the same time, due to stricter environmental requirements there is a need to install equipment to reduce sulphur and nitrogen emissions.

Despite the fact that numerous theoretical and experimental studies described in [16] have been devoted to the oil shale PF technology, still a lot of valuable information is missing. In addition to PF and CFB combustion technologies of oil shale also an attempt was made to apply the vortex combustion (VC), which consists in the generation, in the lower part of the furnace, of a circulatory motion of the gas relative to the horizontal axis (the horizontal vortex) by rearranging the geometry of the combustion air injection and the fuel feeding into the combustion chamber. A detailed description of the effort to apply the VC to oil shale can be found in [17].

To compare CFB and PF technologies, including the efficiencies of desulphurization, the present situation with PF boiler emissions, ash balance and boiler efficiency had to be determined in detail, both at partial and nominal loads. In the frame of the research oil shale firing tests were performed on the boiler TP-101 of the EPP's energy unit No. 5. In the energy unit with a capacity of 200 MW_e the pulverized combustion technology is applied. The TP-101 boiler has four flues and its steam output is 320 t/h with parameters of 14 MPa and 540/540 °C. Some of the characteristics that are attributed to this technology include temperatures as high as 1350–1400 °C within the combustion chamber, the occurrence of reducing atmosphere zones in the furnace and the fine particle fraction of the ground fuel, but also significant features of the thermal conversion of the mineral part of oil shale.

2. Experimental set-up

The major goal of tests was to carry out the analyses of ash and flue gas, as well as verify data obtained in the 1980s – flue gas composition, ash balance and boiler efficiency. The tests were conducted with the oil shale of class P3 (particle size 0–40 mm) from the screening before enrichment from Estonia and Viru mines, and P4 (0–300 mm) fuel from the Estonia mine.

The main characteristics of the boiler during the tests are given in Table 1. The variations of steam pressure and mass flow during all tests are presented as well. It can be seen that the variations are smaller than the marginal values given in the standard EVS-EN 12952-15 (2003) [18].

Table 1. Boiler characteristics

Item	Partial load	Nominal load
Boiler load, MW _{th}	131.0	235.4
Electrical load of unit, MW _e	100.02	192.54
Steam temperature (live/superheated), °C	514.0/509.8	508.9/510
Steam pressure (live/superheated), MPa	12.76/1.02	12.91/2.06
Pressure variation of live steam, %	0.8	0.2
Steam mass flow (live/superheated), kg/s	44.26	85.08/74.93
Mass flow variation of live steam, %	4.2	1.5
Flue gas temperature (after the ESP), °C	181	190

During the tests the essential auxiliaries of the energy unit were registered. The total electricity use of the auxiliary equipment of the unit was 12.23 MW (12.2%) at partial load and 15.47 MW (8.0%) at nominal load.

During the tests the analyses of fuel, ash and flue gas were carried out. The location of ports for collecting samples is shown in Fig. 1. Fuel samples were taken on daily average basis. Ash samples were taken from several ports located in the furnace chamber, super heater (SH), economizer (ECO) and cyclone, and from all three fields of the electrostatic precipitator (ESP). Samples of fly ash for determining the mass division (total suspended particulates PM10 and PM2.5) were taken before the flue-gas fan. All ash samples were taken from both sides (A – left and B – right) of the boiler. The samples were used for determining a detailed chemical composition of cyclone and ESP ashes, including the content of CaO_{free} and CO_{2carbonate}. During the tests the electricity use of the auxiliary equipment of the unit and boiler efficiency were calculated as well.

The results of sample analyses were averaged to reach a representative estimate. Also, during the test the major process parameters of the boiler and unit as a whole were recorded using the plant's standard data acquisition

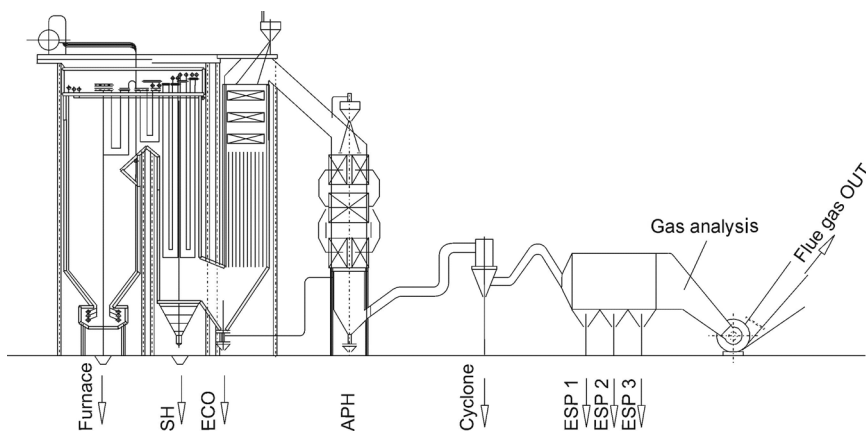


Fig. 1. Boiler TP-101 – sampling points.

system enabling to determine the unit's electricity self-consumption. The temperature and composition of flue gas were measured before the flue gas exhaust fan on both sides of the boiler.

The test at partial (50%; ~158 t/h of primary steam) boiler load was conducted firing oil shale from the Viru mine. During the nominal (100%; ~310 t/h) load test three varieties of oil shale supplied from Viru and Estonia mines were used.

The samples of bottom and fly ash from both boiler sides were taken at nominal and partial loads. The total of 16 ash samples were taken from several ports located in the furnace, super heater, economizer and cyclone, and from all three fields of the electrostatic precipitator (ESP1, ESP2 and ESP3). The ash was taken from the dry flow to ensure representative samples.

2.1. Composition of flue gas

The analysis of combustion gas was carried out at both loads and the sample was taken from the ports behind the ESP. The flow of combustion gas from the boiler is divided into two passes and directed into two ESPs (filters A (right) and B (left)). Gas samples for analyses were taken from both sides of the boiler as the composition of flue gas and ash mass flows in these ducts are different, as a rule. The measurements in both passes were made during 15 minutes. Also, the flow speed was measured periodically and temperature continuously.

The same ports were used for taking fly ash samples to determine the division of the finest particles (PM10 and PM2.5) in flue gas. The composition of flue gas was determined applying an FTIR type analyzer for wet gas, at a temperature of 180 °C. The flue gas moisture content was also determined by a FTIR spectrometer.

3. Results and discussion

3.1. Fuel – oil shale

The oil shale samples were analyzed in laboratories of the Department of Thermal Engineering (DTE) of Tallinn University of Technology and EPP. The local laboratory of EPP determined the daily average heating value and moisture content W_i^f . The DTE laboratory made the ultimate and proximate analysis of the same samples. Table 2 presents the heating values determined

Table 2. Oil shale characteristics

	Partial load	Nominal load
W_i^r , %	12.7	11.6
Q_b^d , MJ/kg	10.9	10.3
Q_i^r , MJ/kg	8.5	8.1
A^r , %	44.3	45.8
$(CO_2)_c^r$, %	16.7	17.2

in a calorimetric bomb (Q_b^d) as well as calculated by general moisture content (Q_i^f). The heating values determined in both laboratories are practically the same.

3.2. The chemical composition of ash samples

The samples were taken at two boiler loads: nominal (100%; ~310 t/h) and partial (50%; ~158 t/h). The composition of fuel and ash (at 815 °C) is presented in Table 3. The nitrogen content in ash samples was below detection limit.

Table 3. Chemical composition of ash, %

	Load, t/h	Furnace	SH	ECO	Cyclone	ESP 1	ESP 2	ESP 3
CO ₂	158	18.71	7.36	5.91	1.92	1.60	1.40	0.93
	310	2.67	1.10	2.87	1.08	1.68	1.46	1.18
C (CO ₂)	158	5.10	2.01	1.61	0.52	0.44	0.38	0.25
	310	0.73	0.30	0.78	0.29	0.46	0.40	0.32
C _{elem}	158	5.71	2.03	1.58	0.31	0.34	0.25	0.18
	310	0.72	0.21	0.68	0.19	0.35	0.25	0.16
S _{elem}	158	1.09	1.75	1.72	1.42	2.51	2.88	3.70
	310	0.83	1.53	1.79	0.98	2.37	2.75	3.42
SO ₃ total	158	2.73	4.38	4.30	3.56	6.28	7.20	9.25
	310	2.08	3.83	4.48	2.45	5.93	6.88	8.55
S _{sulphate}	158	1.02	1.75	1.74	1.44	2.44	2.76	3.65
	310	0.79	1.51	1.77	0.94	2.27	2.66	3.24
SO ₃ sulphate	158	2.55	4.38	4.35	3.60	6.10	6.90	9.13
	310	1.98	3.76	4.41	2.35	5.67	6.64	8.09
SiO ₂	158	12.99	16.25	20.01	23.77	34.41	36.02	41.32
	310	24.58	28.34	26.42	28.74	35.55	37.03	37.98
Fe ₂ O ₃	158	4.66	3.58	4.00	1.58	1.30	1.47	1.16
	310	3.85	4.05	4.17	4.11	3.93	4.08	3.97
Al ₂ O ₃	158	5.98	9.73	11.54	14.45	18.01	21.24	20.34
	310	14.70	8.50	6.85	7.59	9.22	8.89	11.33
CaO	158	57.74	59.08	58.54	57.21	36.04	33.46	28.01
	310	53.38	46.76	45.75	45.70	33.37	28.96	24.67
CaO _{free}	158	16.41	25.07	19.45	23.40	12.28	10.53	6.82
	310	19.79	14.35	15.00	17.31	10.35	9.63	6.28
MgO	158	0.90	2.95	1.04	2.02	1.45	1.09	2.04
	310	5.30	5.27	6.42	6.81	3.36	4.36	3.10
K ₂ O	158	1.16	1.69	1.73	1.93	4.10	5.51	7.49
	310	1.90	2.21	2.19	1.95	5.25	5.54	7.19
Na ₂ O	158	0.24	0.18	0.18	0.21	0.34	1.89	0.56
	310	0.24	0.24	0.22	0.19	0.38	0.41	0.47
Cl	158	0.22	0.16	0.16	0.16	0.22	0.40	0.54
	310	0.10	0.14	0.13	0.18	0.42	0.33	0.50
Loss on ignition, 815 °C	158	19.00	7.90	6.20	2.00	1.40	1.70	1.80
	310	3.00	1.25	2.90	0.90	1.80	1.60	1.70

Table 4. Carbon content in ash samples

Sampling point	Boiler load, t/h	Chemical analysis, %		Calculated, %	
		CO ₂	C _{elem}	CO _{carb}	C _{org}
Furnace	158	18.71	5.71	5.10	0.61
	310	2.67	0.72	0.73	0.01
Super heater	158	7.36	2.03	2.01	0.02
	310	1.10	0.21	0.30	0.07
Economizer	158	5.91	1.58	1.61	–
	310	2.87	0.68	0.78	–
Cyclone	158	1.92	0.31	0.52	–
	310	1.08	0.19	0.29	–
ESP 1	158	1.60	0.34	0.44	–
	310	1.68	0.35	0.46	–
ESP 2	158	1.40	0.25	0.38	–
	310	1.46	0.25	0.40	–
ESP 3	158	0.93	0.18	0.25	–
	310	1.18	0.16	0.32	–

The content of organic carbon in ash samples is given in Table 4 and the extent of carbonate minerals decomposition in various ash samples is presented in Table 5.

Table 5. The extent of carbonate minerals decomposition (k_{CO_2})

Boiler load	Furnace	SH	ECO	Cyclone	ESP 1	ESP 2	ESP 3
Partial	0.59	0.85	0.87	0.96	0.95	0.95	0.96
Nominal	0.94	0.97	0.92	0.97	0.95	0.95	0.96

The content of free lime (CaO_{free}) in ash samples taken from various fields of the ESP was 6–12%. Considering the filter balance the content was 10.1% at full load and 11.8% at partial load. The content of organic carbon is low as is typical of the pulverized combustion of oil shale.

The tests indicated that the extent of carbonate minerals decomposition (k_{CO_2}) at the nominal load is in the range of 0.92–0.97. At the partial load the decomposition is somewhat lower in ashes of the super heater and economizer – 0.85 and 0.87, respectively, and is substantially lower in bottom ash (0.59).

The size distribution of ash is presented in Table 6. The residue R₂₀₀₀ of the bottom ash on the sieve with an aperture of 2000 μm at the partial load was only 0.05%.

There are no significant differences in composition between ashes from tests at normal and partial loads. Still, the higher variability of the ash from the partial load test can be noticed. Also, the median size of the ash samples taken from the furnace, super heater and economizer at the full load is larger compared to the partial load ash.

Table 6. The size distribution of ash, % of cumulative oversize

Residue, R(x)	Boiler load, t/h	Furnace	Super heater	Economizer	Cyclone
0.500	158	14.44	7.62	1.02	–
	310	14.33	1.11	0.44	–
0.355	158	26.02	5.86	2.07	0.04
	310	27.46	17.99	3.02	0.14
0.180	158	57.92	39.90	24.26	4.83
	310	61.79	50.98	18.06	6.68
0.125	158	69.84	62.21	47.35	17.19
	310	75.62	66.89	33.69	22.35

For characterizing ashes and for drawing up an ash balance the bulk and aggregate densities of ashes were determined. Table 7 presents the aggregate densities determined for ashes from the super heater, economizer, cyclone and ESP 1. In order to obtain pure ash samples and exclude the falling of ash deposits from heating surfaces after automatic cleaning when ash sampling was performed, the ash samples were sieved using a 3 mm sieve before determination of density. The mass share of the sieved particles was 2–16%.

Table 7. Aggregate density of ash

Sampling point	Density, ρ , g/cm ³
Super heater	2.57
Economizer	2.60
Cyclone	2.71
ESP 1	2.63

The aggregate densities were used to estimate the ash mass flow. There was no variation of aggregate density at different boiler loads. Therefore, the average densities are presented by ash type (Table 7). The bulk densities determined by the DTE laboratory are given in Table 8.

Table 8. Bulk density of ash flows, g/cm³

Sampling point	Partial	Nominal
Furnace (bottom ash)	1.230	1.128
Super heater	1.201	1.209
Economizer	1.274	1.335
Cyclone	1.420	1.546
ESP 1	1.086	1.120
ESP 2	0.945	0.953
ESP 3	0.817	0.794

3.3. Ash balance

The method based on pulp (a mix of ash and water) was applied to determine the mass flow of ash from the super heater, economizer, cyclone and ESP

fields 1 to 3. The method described in detail in [17] includes the determination of ash flow rate by measuring pulp volume and mass.

The ash mass flows were determined for samples taken from under the super heaters, economizers and cyclone, and from ESP fields 1 to 3 at partial and nominal loads. The samples were taken twice at both loads and the mass flow was determined in every sample point three times. Therefore, the calculated value of the flow is the mean of six measurements. The results were used for drawing up the ash balance. The ash input into the boiler was calculated on the basis of the fuel flow by applying an indirect balance method. The amount of furnace ash was calculated subtracting the total volume of ash of super heaters, economizers, cyclone and all three fields of ESP from the volume of boiler input ash.

The ash balance at nominal load is presented in Fig. 2. The total share of ash from the furnace, super heaters and economizers is 51%. The results differ from those reported in [16] because four old ESPs have been replaced with three new ones. Also, the pre-precipitator chamber has been removed before the cyclone.

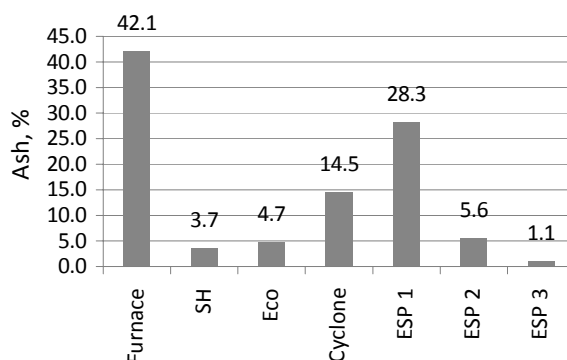


Fig. 2. Ash balance at nominal load.

3.4. Boiler heat balance

In the full-scale experimental study heat balance and thermal efficiency estimations of the TP-101 boiler were made on the basis of the standard [18] by using the indirect method taking into account the specific characteristics of oil shale as a fuel. The amount of heat released, ash content and flue gas amount during combustion of oil shale depend strongly on the endothermic and exothermic processes taking place in the mineral part of the fuel [16]. These processes include the decomposition of calcite and dolomite, oxidation of FeS_2 , sulfation of CaO and formation of new minerals. A more detailed description of the calculation of heat amount and ash content can be found in [7]. Combustion flue gas mass and volume and carbon dioxide ratio to fuel mass were calculated. For calculations the following equations were used:

1) flue gas mass (dry gas), kg/kg:

$$\mu_{\text{God}} = 12.5122\gamma_{\text{C}} + 26.3604\gamma_{\text{H}} - 3.3212\gamma_{\text{O}} + 1.0\gamma_{\text{N}} \\ + \left[(1 - \eta_{\text{S}})1.9953 + 3.2947 \right] \gamma_{\text{S}} + k_{\text{CO}_2} \gamma_{\text{CO}_2},$$

where γ_{C} , γ_{H} , γ_{O} , γ_{N} , γ_{S} , γ_{CO_2} are carbon, hydrogen, oxygen, nitrogen, sulfur and carbonate carbon dioxide contents in fuels, respectively, kg/kg; η_{S} is the efficiency of desulfurization (p. 8.3.5 in [18]); k_{CO_2} is the extent of carbonate mineral decomposition [19];

2) flue gas volume (dry gas), m³/kg:

$$V_{\text{God}} = 8.8930\gamma_{\text{C}} + 20.9724\gamma_{\text{H}} - 2.6424\gamma_{\text{O}} + 0.7997\gamma_{\text{N}} \\ + \left[(1 - \eta_{\text{S}})0.68172 + 2.6325 \right] \gamma_{\text{S}} + 0.509\gamma_{\text{CO}_2} k_{\text{CO}_2}.$$

3) carbon dioxide content ratio to fuel mass (dry gas), kg/kg:

$$\mu_{\text{CO}_2_0} = 3.6699\gamma_{\text{C}} + 0.0173\gamma_{\text{H}} - 0.0022\gamma_{\text{O}} \\ + \left[(1 - \eta_{\text{S}})0.001 + 0.0017 \right] \gamma_{\text{S}} + k_{\text{CO}_2} \gamma_{\text{CO}_2}.$$

All heat balance calculations were made for normal conditions: $t_{\text{r}} = 0$ °C, $p_{\text{r}} = 101\,325$ Pa. According to the above-mentioned EVS-EN standard the boiler efficiency at nominal load was 86.4% (Table 9).

Table 9. Boiler efficiency

Item	Value	
	kW	%
Heat input		
Heat from fuel combustion	264 599	97.2
Physical heat of fuel	846	0.3
Input heat of combustion air	6 431	2.4
Electrostatic precipitator	432	0.2
Total	272 308	100.1
Useful heat capacity	235 233	
Loss with flue gas	32 360	11.9
Loss due to unburned fuel (CO)	30	0.0
Bottom ash loss	2 979	1.1
Fly ash loss	0	0.0
Loss due to radiation	1 707	0.6
Total	37 076	13.6
Heat efficiency		86.4

3.5. Flue gas

The composition of flue gas was determined after the ESP (see Fig. 1). Additionally, the EPP personnel measured the flue gas oxygen content after the air preheater. The average concentration of major emission gases are given in Table 10.

The series of four tests were performed at both nominal and partial load. The test results (Table 10) indicate that the share of flue gas components depending on boiler load changes. At partial load the oxygen content in flue gas is twice that at full load. At full load the content of other components in flue gas is substantially higher as compared to that at partial load. For example, the content of SO₂ at full load is approximately twice that at partial load.

Table 10. Concentration of main pollutants in flue gas after the ESP (6% O₂)

Boiler load	O ₂ , %	CO ₂ , %	CO, ppm	NO, ppm	SO ₂ , ppm	HCl, ppm
Partial	12.5	12.9	17.2	145.6	938.3	55.9
Nominal	6.1	12.7	22.7	109.7	1059.1	60.2

The content of finest particles of fly ash together with its mass division (PM_{10/2.5}) after the ESP is an important indicator of flue gas composition. This is the fly ash that cannot be caught by the final section of the ESP and, as a result, is emitted into the ambient air.

The mass division of fly ash after the ESP was determined in three tests at both boiler loads (Fig. 3). As predicted, the content of finest ash particles (<2.5 μm) is higher at nominal load.

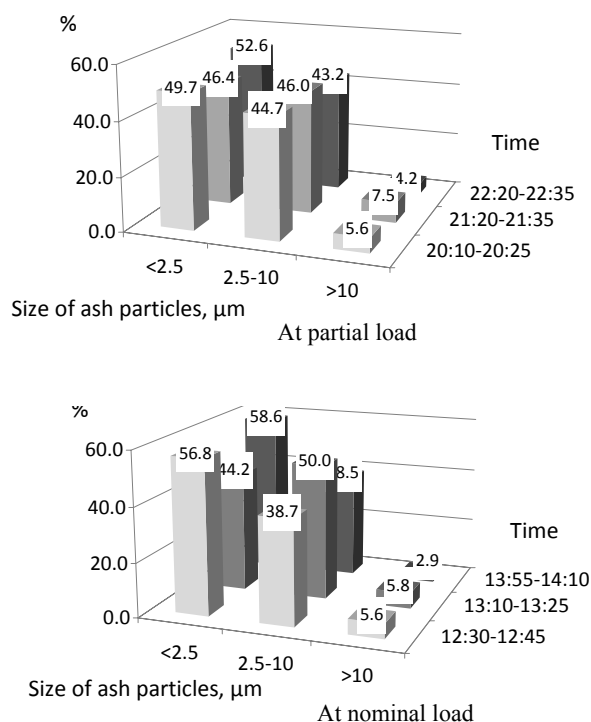


Fig. 3. Fly ash mass distribution after ESP.

3.6. Specific consumption and emission of the energy unit

Specific mass flow indicators of fuel and ash, CO₂, CO and SO₂ emissions both per useful heat (MWh_{th}) and gross electricity production (MWh_e^{br}) are given in Table 11. The specific indicators of fuel and ash per production unit obtained experimentally for the first boiler of the unit were assumed to be applicable for the second boiler as well. In Table 12 there are two values of the CO₂ emission – based on sample measurements, and calculated on the basis of fuel composition.

The heat rate of the unit was 2.49 MWh_{th}/MWh_e^{br}, corresponding to the gross energy efficiency of 40.16%.

Table 11. Specific indicators of fuel consumption and ash emissions

Indicator	Unit	Value
Oil shale consumption per useful heat	g/kWh _{th}	489
Ash formation per useful heat	g/kWh _{th}	223
Oil shale per electricity (gross)	g/kWh _e ^{br}	1219
Ash emission per electricity (gross)	g/kWh _e ^{br}	555

Table 12. Specific emission indicators

Pollutant	Per useful heat, kg/MWh _{th}	Per electricity (gross), kg/MWh _e ^{br}
CO ₂ ¹	391	974
CO ₂ ²	428	1066
CO	0.045	0.111
SO ₂	4.77	11.89

¹ Calculation based on measured percentage of CO₂ with calculated volume of dry gas.

² Calculation based on fuel composition.

4. Conclusions

The data from the experimental tests conducted on the high-pressure PF boiler TP-101 indicate that the gross thermal efficiency of the boiler is 86.4%. Regarding emission into air, the average concentration of NO_x and SO₂ emissions at stable load varied insignificantly. The test at partial and nominal loads showed that the specific emission of SO₂, CO₂, CO, NO and HCl at full load was essentially higher, e.g. the content of SO₂ was almost twice that at partial load. Also, the content of fine particles (<2.5 μm) of ash after the ESP was higher at nominal load.

During the test, the distribution of the ash amount at different boiler locations was experimentally obtained. The bottom and ESP ashes are the main contributors to the ash flow. The experimental results show that the present situation differs from the designed one as four old ESPs have been

replaced with three new ones and the pre-precipitator chamber has been removed before the cyclone.

The specific consumption of oil shale per useful heat and gross electricity production was 0.489 t/MWh_{th} and 1.219 t/MWh_e^{br}, respectively. The same indicators for ash formation were 0.223 t/MWh_{th} and 0.555 t/MWh_e^{br}.

The heat rate of the unit was 2.49 MWh_{th}/MWh_e^{br}, which corresponds to the gross energy efficiency of 40.16%.

The results of analysis are a good basis for future research and development projects. Also, they can be used to decide on the future operation of PF units at Narva PP.

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