

COMBUSTION EXPERIENCE OF ESTONIAN OIL SHALE IN LARGE POWER PLANTS

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ABSTRACT

By the mid-1950's building in Estonia a new Balti Power Plant (BPP) firing local oil shale was decided. Based on the operation experience of mid-pressure pulverised oil shale boilers and their research it had become clear that Π -shaped boilers firing coal or brown coal are not suitable for oil shale. Thus, the Taganrog Boiler Manufacturing Factory in Russia, in cooperation with several former Soviet Union research institutions and the Tallinn University of Technology (TUT, former Tallinn Polytechnic Institute), developed a new oil shale boiler TP-17 with steam output of 220 t/h (10 MPa, 540°C). Based on practical experience, new more powerful boiler TP-67 with three gas passes and steam output 320 t/h (14 MPa, 540/540°C) was created.

Another power plant – the Eesti Power Plant (EPP) equipped with 200 MW_e double units (EPP, 1600 MW_e) – was launched in 1969-1973. Based on the knowledge and experience acquired in the course of TP-17 and TP-67 operation a new pulverised oil shale boiler – TP-101 – was created for these units.

The total of 42 pulverised firing (PF) oil shale boilers TP-17, TP-67 and TP-101 were launched at oil shale power plants in Estonia in 1959-1973.

Estonian oil shale proved to be a fuel with such complicated properties that no good operating boilers could be developed despite all the modern knowledge of the day applied. Nor could the conducted reconstructions ensure that the boilers operate with the parameters stipulated in the initial project. The boilers' operating capacity remained at 80-90% of the planned values. The main problems that could not be liquidated were the intensive fouling of the heating surfaces with hard fly ash deposits and the high-temperature corrosion and wear of steam superheaters. Due to the intensive fouling and corrosion of the heating surfaces, the efficiency factor remained at 28-30%.

In the early 1990's the need to renovate oil shale power plants became evident – as the operating period of the older heat engineering equipment exceeded the original project operational age more than twice. The oil shale PF technology had already exhausted its development potential. Yet by that time the fluidised bed (FB) combustion had earned worldwide recognition and different companies had already implemented at many locations all over the world FB boilers working on various fuels. Results of the completed test combustion and laboratory studies indicated that Estonian oil shale is well-combustible with the circulating fluidised bed (CFB) technology. The international procurement competition for the complex renovation of two 200 MW_e energy units (one in EPP and one in BPP), including the construction of four (two per each unit) CFB oil shale boilers won the Foster Wheeler Energia OY. The new 215 MW_e energy units were launched in 2004.

Operation experience of the CFB boilers show significant advantages compare to the old PF boilers. The new ones have – higher efficiency, respectively smaller fuel consumption and sub

stantially lower amounts of harmful gas components emitted into the atmosphere ($\text{SO}_2 < 20 \text{ mg/Nm}^3$, $\text{NO}_x < 160 \text{ mg/Nm}^3$, CO_2 920-950 t/GWh and fly ash emission 25-30 mg/Nm³).

The first exploitation experience of the CFB boilers allow to state significantly better situation in matter of fouling and high-temperature corrosion. The intensive fouling and the high-temperature corrosion and wear of boiler heating surfaces taking place in PF boilers had not appeared in CFB boilers.

OIL SHALE PF BOILERS AT ESTONIAN POWER PLANTS

By the mid-1950's, when the decision was made to build in Estonia a new and large Balti Power Plant operating on oil shale, it had become clear based on the experience of service of medium-pressure pulverised oil shale boilers and their research by Öpik [1] that Π -shaped boilers operating on mineral coal or brown coal are not suitable for oil shale. Thus, the Taganrog Boiler Manufacturing Factory, in cooperation with several Soviet Union research institutions and the Tallinn Polytechnical Institute, developed a completely new oil shale boiler TP-17, with its project stipulating steam output of 220 t/h and steam parameters – pressure 10 MPa and temperature 540°C [1, 2, 3]. The first TP-17 boiler was launched at the BPP in late 1959 and the last – in 1963. The essential peculiarities of TP-17 when compared to coal boilers were four vertical gas flues and placement of the predominant section of the superheater in the gas flue that was descending partly in cross-flow and partly in longitudinal-flow screens. With such boilers (the total of 18 units) were equipped the three first stages of the power plant being constructed and the total capacity was 800 MW_e. When the fourth stage of the BPP, equipped with 200 MW_e energy units (double units), was being built, a new recently created and more powerful boiler type was implemented, TP-67. It had three gas passes and the project stipulated its steam output to be 320 t/h and steam parameters – pressure 14 MPa and steam temperature 540/540°C. TP-67 was developed in view of the experience obtained in the course of TP-17 service. The first energy unit equipped with TP-67 boilers was launched in 1963 and the last, fourth – in 1966.

When it was decided in 1964 to construct another power plant equipped with 200 MWe double units, the Eesti Power Plant of 1600 MWe, a new pulverised oil shale boiler – TP-101 – was created for these units, based on the knowledge and experience acquired in the course of TP-17 and TP-67 service. The TP-101 boiler had four flues and its estimated steam output and steam parameters corresponded to those of TP-67 (320 t/h, 14 MPa and 540/540°C). The EPP units (the total of 8 units) were launched in 1969-1973. The total of 42 pulverised firing (PF) oil shale boilers TP-17, TP-67 and TP-101 [2, 3] were launched at oil shale power plants in Estonia in 1959-1973 (Fig. 1).

Unfortunately, Estonian oil shale proved to be a fuel with such complicated properties that no ideally operating boilers could be developed despite all the modern knowledge of the day applied. Nor could the conducted reconstructions ensure that the boilers operate with the parameters stipulated in the initial project. The boilers' operating capacity remained at 80-90% and economic efficiency at 75% of the planned values. Those main problems that could not be liquidated were the intensive fouling of the boiler heating surfaces with hard fly ash deposits (Fig. 2) and the high-temperature corrosion and wear of steam superheaters caused by oil shale ash [2, 3, 4]. To extend the boiler work period and improve heat reception, the heating surfaces had to be cleaned. That regularly was done in many ways when the boilers were operating (vibrocleaning, blowing with steam and water, etc.) but, despite research carried out to find suitable cleaning regimes and develop new cleaning devices, no completely satisfactory solution was ever found that would guarantee the boilers' operating with the stipulated parameters.

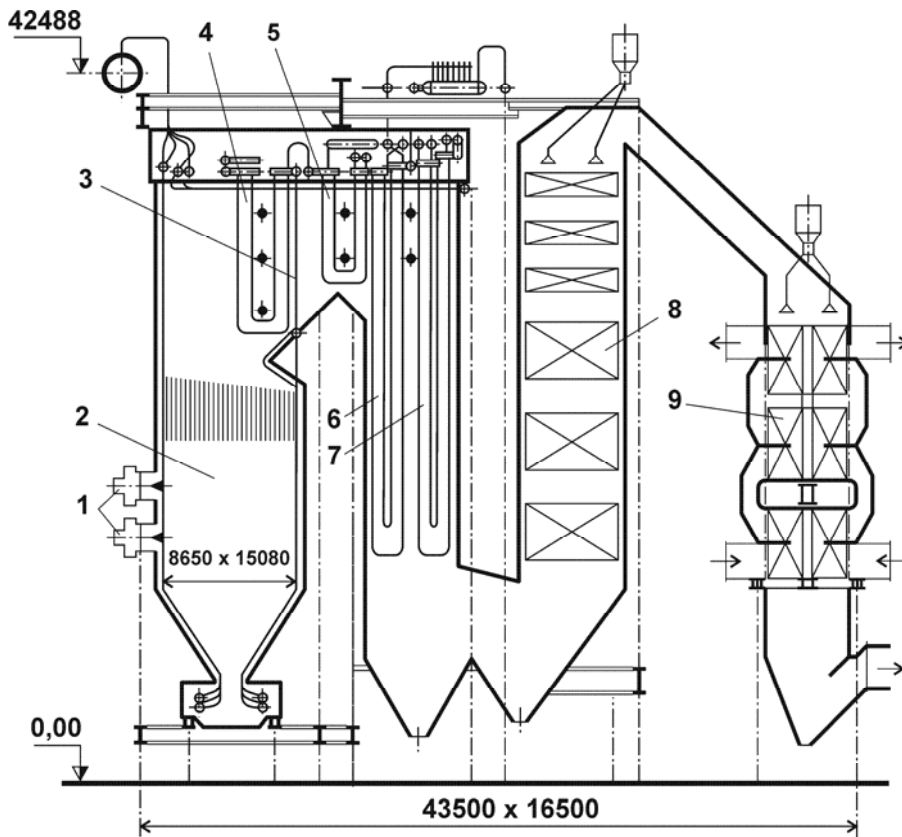


Fig. 1. PF boiler TP-101. 1 – burners, 2 – furnace, 3 – outlet screen, 4 – furnace platen superheater, 5 – intermediate platen superheater, 6 – hanging platens of primary superheater, 7 – hanging platens of reheater, 8 – economizer, 9 – air preheater [3].

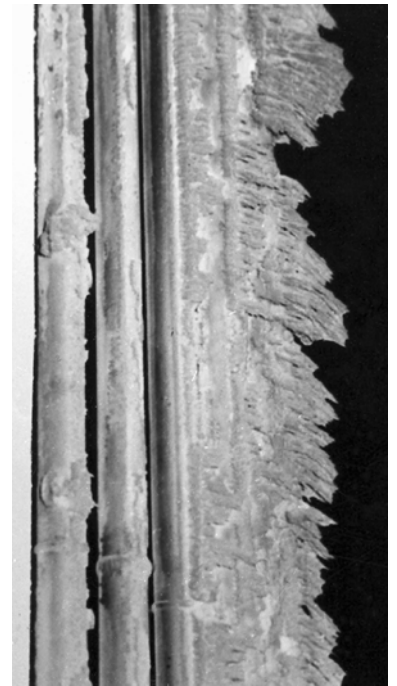


Fig. 2. Oil shale ash hard deposits on the superheater tubes

This was so because it was impossible to avoid the emergence and rapid growth of deposits and the heating surfaces would become contaminated once more as soon as the latest cleaning cycle had been completed. In addition to this, the cleaning efficiency was limited due to the fact that such intensive cleaning increased the corrosive-erosive wear of the boiler heating surfaces. All this resulted in the energy blocks working at lower steam temperatures (the steam temperature when exiting the boiler: 515-520°C) and loads (180 MW_e instead of planned 200 MW_e) than envisaged. Although highly alloyed steels were used in the heating surfaces operating at higher temperatures to decrease the corrosion and wear of the heating surfaces, repair work volumes for the boilers were large (for each instance of capital repairs, thousands of worn out sections had to be replaced in the boiler pipes). As a result of all this, service and repair costs were very substantial. Due to the intensive fouling and corrosion of the boiler heating surfaces, oil shale power plants could not achieve the output envisaged in the initial project and their efficiency factor remained at 28-30%.

Moreover, the oil shale power plants' work exhibited other deficiencies. The first aspect that should be noted here is the high SO₂ content in flue gas – despite the 75-80% extent of sulphur binding, 1500-2000 mg/Nm³ (mg per normal cubic meter) of it was formed in the boiler. Also the CO₂ content in the oil shale power plant flue gas was larger than that at power plants operating on other fossil fuels. That was due to the considerable content of carbonaceous compounds in the Estonian oil shale mineral part and as they were combusted and decomposed, they would discharge not only the CO₂ that is created when the fuel organic matter burns, but an additional CO₂ amount as well. Substantial had also been the ash amount (>1500 mg/Nm³) emitted into the at

mosphere along with the flue gas but the latter deficiency was successfully overcome in the recent years due to the installation of new electrostatic precipitators.

SEARCH FOR A NEW OIL SHALE COMBUSTION TECHNOLOGY

When in the late 1980's and early 1990's the issue was raised of the need to renovate the oil shale power plants – as the operating period of the older heat engineering equipment at the power plants exceeded the original project operational age more than twice – it was already evident that the oil shale PF technology had already exhausted its development potential. A new technology had to be found for the purpose of substantially improving the power plants' work. Such technologies as the low-temperature vortex furnace, bubbling-fluidised bed furnace, etc., had been previously tested at the oil shale power plants but proved inefficient. Yet by that time the fluidised bed (FB) combustion had earned worldwide recognition and different companies had already implemented at many locations all over the world FB boilers working on various fuels and suitable for power plants.

Regrettably, the companies that manufactured FB boilers lacked serious experience with oil shale. In view of the experience obtained with PF oil shale boilers, indicating that boilers designed for other fuels were quite unsuitable for oil shale combustion and the behaviour of the Estonian oil shale mineral part can result in serious problems if used in such boilers, Eesti Energia Ltd (EE) came to the conclusion that, prior to making the final decision on implementing FB boilers for oil shale at Estonian power plants, the corresponding research and test combustions must be conducted on FB equipment of different foreign companies. Specialists from the TTU's Department of Thermal Engineering and EE participated in these test combustions.

The first Estonian oil shale test combustion was conducted in 1994. It took place in Finland at the Hans Ahlstrom Laboratory (later Foster Wheeler) on the PF-600 Pyroflow test device with the thermal capacity of ~ 1 MW [5]. The goal of that work was to obtain initial data for the design of a 100 MW_{th} test FB boiler for the Kohtla-Järve Thermal Power Plant. The oil shale to be combusted there, with the maximal particle size of 25 mm, totalling about 160 tons, was prepared and delivered to Finland. The test combustion was carried out at the atmospheric pressure and in several regimes and, in addition to combustion tests and measurements taken at the test board, laboratory studies were conducted of the obtained ash and deposit samples. The latter took place both at the Hans Ahlstrom Laboratory and at the TUT.

Results of the completed test combustion and laboratory studies indicated that Estonian oil shale is well-combustible with the circulating fluidised bed (CFB) technology. The furnace temperature regimes could be regulated well between 800-900°C and the temperature field was even along the furnace height. The optimal combustion temperature was 850°C. Yet the classic fluidised ("bubbling") bed proved unsuitable for Estonian oil shale as in that regime the oil shale volatiles content was large (80-90%), thus they were carried out of the bed and the combustion zone appeared above the bed, making the furnace regime practically uncontrollable. This was the decisive factor and the greatest part of the combustion tests were carried out in the CFB regime. It was confirmed that the ash flying out of the combustion chamber was considerably more fine-grained [6] than fly ash in pulverised oil shale boilers, with the extent of carbonates decomposition was only approximately 80%. Especially noteworthy was the fact that almost all sulphur was bound by ash already while in the furnace, which is why the SO₂ content in the flue gas discharged from the device remained under 5 ppm (< 15 mg/Nm³). Ash refinement and the almost complete lack of SO₂ in the flue gas was the reason why only easily removable, soft and fragile deposits formed on the device's convective heating surfaces. All of this allowed to make the forecast that, when FB boilers were implemented at oil shale power plants, these power plants

would become more environmentally-friendly and the operating conditions of the boiler heating surfaces would improved compared to those in PF boilers [7].

The next two oil shale FB test combustions were carried out in 1996. First in Germany, at the Lurgi Lentjes Babcock Energietechnik GmbH company, at the $\sim 1 \text{ MW}_{\text{th}}$ atmospheric pressure test device [5]. This test combustion was carried out in accordance with the PHARE programme. The second test combustion was carried out by ABB Combustion Engineering in cooperation with the University of British Columbia on a test device of the university in Canada, Vancouver [8]. The tests were with a relatively small capacity ($\sim 150 \text{ kW}$), the test device was working at the atmospheric pressure.

The results of studies coincided very well with those obtained on the Ahlstrom company's test device, thus further confirming the conclusions reached earlier – that oil shale is well-combustible in the CFBC regime, the SO_2 content in the flue gas is essentially zero ($< 5 \text{ ppm}$) and the deposits forming on the convective heating surfaces of FB boilers are non-bound and can be easily removed [9].

The data acquired in the course of the test combustions allowed the TUT's Department of Thermal Engineering (DTE) in cooperation with EE to formulate the basic recommendations that should be taken into account when designing FB boilers operating on Estonian oil shale [10].

The results of the test combustions can be summed up in the following way:

– Combustion efficiency and stability

The tests confirmed the high efficiency and stability of oil shale combustion.

– Harmful atmospheric emissions

Special attention was given to studying SO_2 and NO_x emissions. It is known that the quite high level of sulphur dioxide emissions during pulverised firing is caused by a high combustion temperature (up to 1450°C in the furnace centre) and a relatively short period when fuel particles are in the flues (a few seconds) – neither of the two aspects facilitates binding of sulphur compounds with calcium. Yet the amount of calcium compounds in oil shale is almost 10 times larger than it would be theoretically needed for complete binding of sulphur compounds (unfortunately, the binding coefficient achieved is merely 80%).

As for the CFBC technology, due to the substantial thermal capacity of the circulating fuel and ash mass, it is possible to considerably decrease the combustion temperature and make it optimal for binding sulphur compounds (about 850°C). At the same time, as the fuel and ash mass circulates repeatedly in the boiler, it provides sufficient time for the sulphur binding reactions to happen. The tests demonstrated that in such conditions the flue gas practically lack sulphur dioxides.

Also the nitrogen dioxide concentration in the flue gas during the tests was somewhat smaller than in the PF conditions. This is caused by a lower combustion temperature, too.

– Fouling of the heating surfaces

In the PF conditions, the heating surfaces become heavily polluted with hard bound ash deposits. The mechanism and conditions necessary for their development have been thoroughly researched. In the course of the CFBC technology tests it was discovered that no hardbound deposits develop, but instead fragile scattered deposits weakly connected to the heating surfaces and they can be relatively easily removed from the heating surfaces.

Such a qualitative change is mainly caused by the lower combustion temperature of the CFBC technology and the lack of sulphur dioxides in the combustion gas.

As a result, the heating surfaces in a FB boiler function in a considerably more efficient manner and they can be cleaned by applying methods that spare the metal structure.

– High-temperature corrosion of the heating surfaces

In FB boilers the heating surfaces succumb to high-temperature corrosion mainly due to the effect of KCl contained in deposits – it develops during the combustion process as the chlorine in the organic part of the fuel is burned. At high temperatures KCl is in the flue gas in the vaporised state and it becomes condensed on the heating surfaces, forming a dense, chlorine-rich base layer that in high-temperature ($> 450^{\circ}\text{C}$) heating surfaces causes intensive metal corrosion.

It was determined during the tests that chlorides concentrate mainly in finer ash fractions that pass the gas route along with the flue gas. In thicker ash fractions (bottom ash and circulating ash) the chloride content is smaller by a magnitude.

As the FB technology allows usage of ash heat exchangers plugged into the ash circulation systems, the proposal was made to remove all high-temperature heating surfaces from the convective flue of the flue gas and place them inside the ash heat exchangers where the heating surfaces will only come into contact with thicker ash with low chloride content.

By implementing such a technical solution, it becomes possible to substantially decrease high-temperature corrosion of the boiler heating surfaces and increase boiler reliability.

– Erosion of the heating surfaces

The analyses of the ash samples obtained in the course of the tests showed that ash particles in FB boilers are relatively soft and only slightly abrasive and the erosive wear characteristic of PF boilers should not be expected to occur when the FB technology is used.

As a result of the extensive studies and oil shale combustion tests it was concluded that the best available modern technology of Estonian oil shale combustion is atmospheric CFB combustion and thus the foundation was laid for introducing a new generation of oil shale boilers.

CFB BOILER – FOSTER WHEELER

Foster Wheeler has recently introduced two major improvements to the CFB technology by introducing the new compact design, where the solids separator has become an integrated part of the combustion chamber structure, and the integrated heat exchanger (INTREX). The solids separator, the re-circulation system and the furnace are now built as integrated cooled panels. This heat exchanger is located in the lower part of the combustion chamber, outside the main combustion area but as an integrated part of the furnace (Fig. 3). It's most pronounced advantage is its location in shelter from the main combustion and produced flue gas, which generally contain the harmful components in the most active form. Applying this heat exchanger as a superheater enables high superheating temperatures due to the protection from any possibly corrosive environment. The INTREX superheater allows effective utilization of fuels with higher chlorine contents: fuels which in conventional designs would cause corrosion of superheater tubes [11].

Based on the test results, Foster Wheeler CFB technology with compact separators and INTREX was selected to offer for oil shale combustion. The specific properties of the fuel, however, re

quired significant modifications to the standard design of a CFB. The most important of these modifications were [12]

- grid design for gentle fluidization, to minimize the fines formation from the friable ash,
- hanging convective superheaters with Foster Wheeler spring hammers for soot blowing, to allow frequent cleaning without excessive steam consumption,
- acoustic soot blowing of the economizers,
- low combustion temperature, $<850^{\circ}\text{C}$, to decrease ash friability and to reduce calcination of the limestone in ash,
- carefully selected steam temperatures for each phase of superheaters, and
- pneumatic fuel feeding into furnace.

The resulted design is shown in Fig. 3.

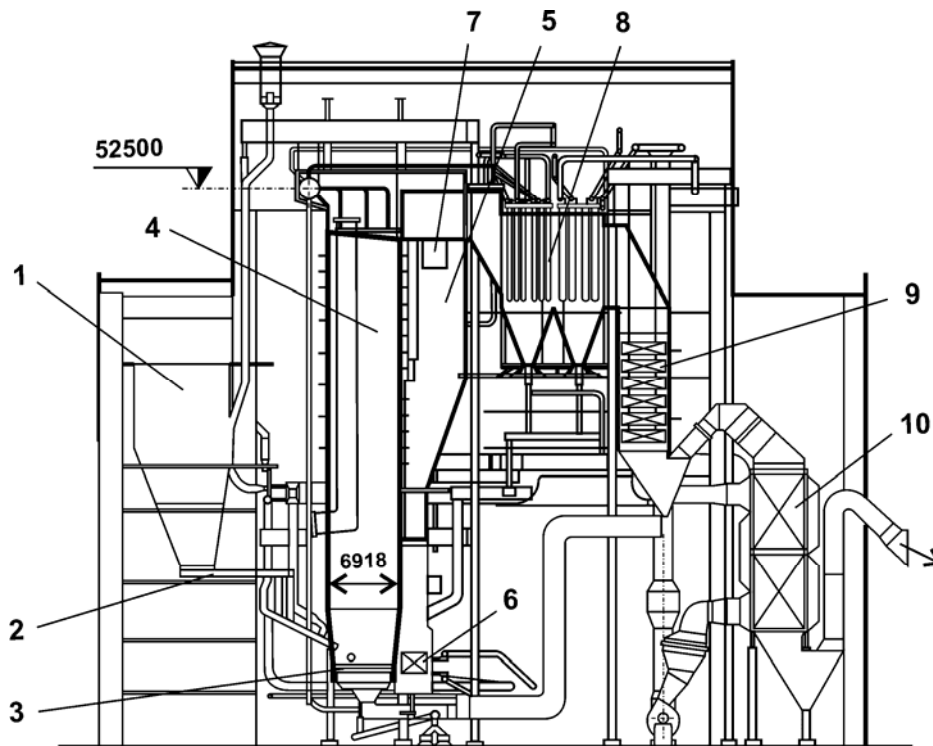


Fig. 3. Oil shale fired CFB boiler. 1 – raw fuel bunker, 2 – fuel feeder, 3 – grate, 4 – furnace chamber, 5 – separating chamber, 6 – fluidized bed internal heat exchanger, 7 – separator, 8 – superheater, 9 – economizer, 10 – air preheater [3].

OPERATIONAL PRACTICE OF CFB UNITS

The average annual values for the main operational characteristics of the new boilers up to the end of 2005 are presented in Table 1.

Both units have operated successfully over a range of loads, from minimum to maximum load, and recorded high availability.

On the basis of the analyses conducted so far of the operational parameters of the new FB boilers, especially of the dynamics of the flue gas, it can be stated that in the FB technology conditions the intensity of the fouling of the heating surfaces remains low and apparently does not have a considerable effect on the boiler's operation, Fig 4 and Fig. 5.

Table 1. Key operating parameters of the new CFB units

Parameter	Meas. Unit	Eesti PP Energy unit 8		Balti PP Energy unit 11
		2004	2005	2005
Electricity generation (Gross)	GWh	1182.1	1169.6	1040.3
Electricity generation (Net)	GWh	1074.2	1058.6	914.5
Auxiliary power	%	10.2	9.6	11.5
Boiler operation hours:	H	6140	5990	5584
	H	6098	6150	5717
Turbine operating hours	H	6333	6339	5870
Turbine average capacity	MW _e	181.4	184.0	173.0
Turbine Min. capacity	MW _e	97.5	87.4	90.8
Turbine Max. capacity	MW _e	214.2	215.2	213.2
Standard fuel consumption	g/kWh	364.8	347.2	377.6
Efficiency	%	34.0	35.5	34.0
Heat rate	MJ/kWh	10.685	10.169	10.577
Oil shale consumption	Tone	1 300 290	1 266 886	1 159 271
Oil shale calorific value (LHV)	MJ/kg	8.477	8.463	8.823

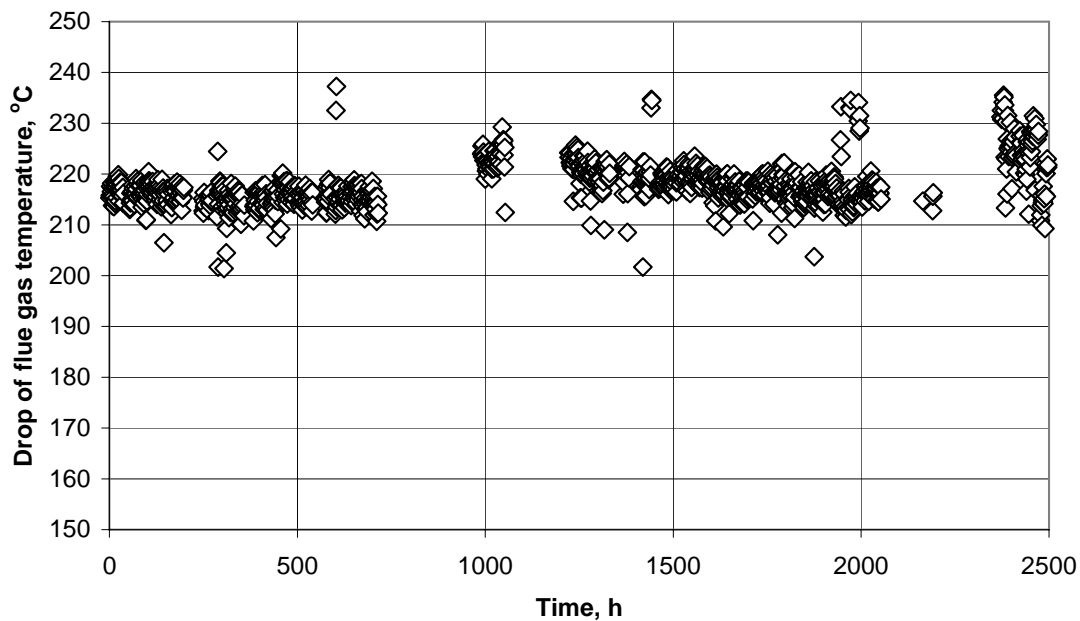


Fig. 4. EPP, boiler 8-1. Temperature drop of flue gas in convective heating surface bundles, between Dec. 9, 2004 and March 23, 2005 at a steam production rate 85-95 kg/s.

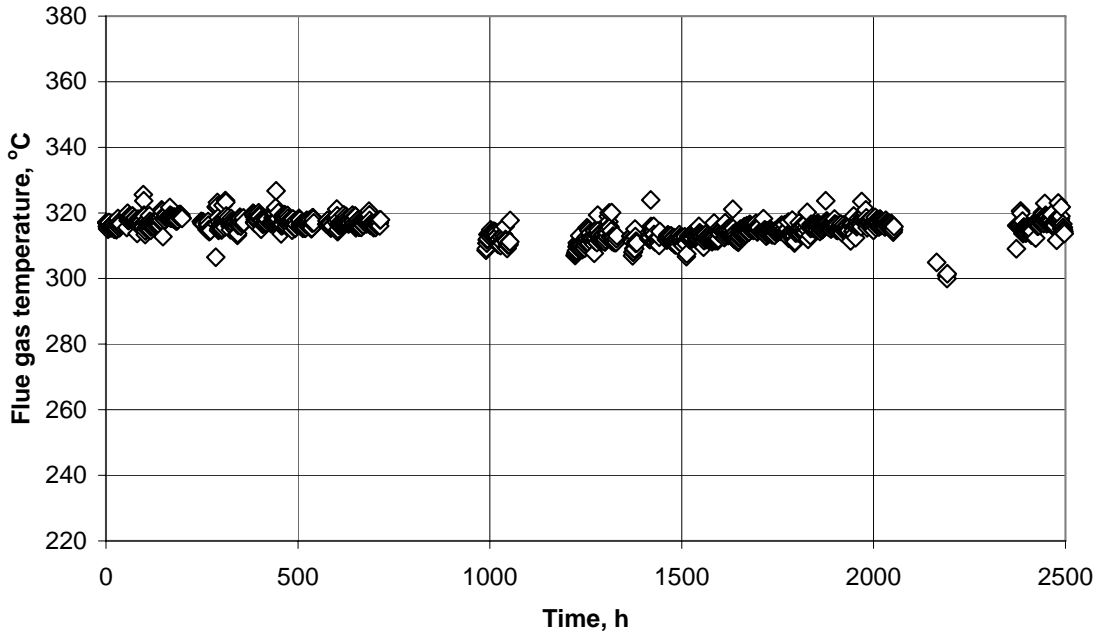


Fig. 5. EPP, boiler 8-1. Average flue gas temperature after the economizer, between Dec. 9, 2004 and March 23, 2005 at a steam production rate 85-95 kg/s.

EMISSIONS FROM THE RENOVATED ENERGY UNITS

The level of the environmental atmospheric emissions from the energy unit has been substantially lower than the strict emissions norms stipulated by the European environmental regulations. It should be noted that the sulphur dioxide emissions level is actually over 10 times lower than the enforced boundary limit of 200 mg/Nm³ – it is only 10-20 mg/Nm³. Almost 2 times lower than the boundary limit of 200 mg/Nm³ is the level of nitrogen dioxides, below 160 mg/Nm³. Fly ash emissions have not exceeded the enforced limit of 30 mg/Nm³.

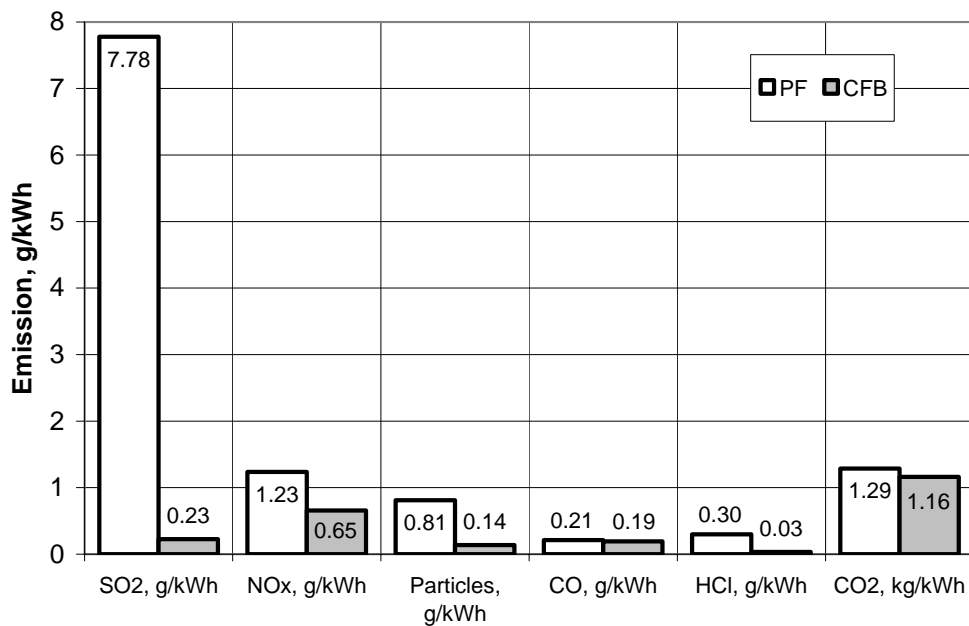


Fig. 6. Emissions to net power unit at Estonian oil shale combustion PF versus CFB firing.

As for the ash from FB boilers, TUT's DTE has carried out initial analyses of ash fractions of FB boilers. The results allow pointing out the following differences regarding ash: the bottom ash in FB boilers contains a noteworthy amount of coarse (> 10 mm; 4-5%) particles while the free lime content is lower than in the ash of PF boilers. The free lime content in all ash fractions examined by TUT's DTE was below 10% (fluctuating at 5.70-8.40%) while the free lime content in the ash of PF boilers is on average 10-30%, depending on various ash size fractions. The lower free lime content in the ash of FB boilers is also confirmed by the extent of carbonates decomposition calculated by TUT's DTE on the basis of the ash analyses – it corresponds well with the results of the tests of block 8 of the Eesti Power Plant conducted by Elektrowatt-EKONO [13], in accordance with which the extent of carbonate decomposition in FB boilers fluctuates on average at 70-75%. In coarser ash fractions the extent of carbonate decomposition can even be below 15%. As for the sulphur in the fuel, it is practically completely bound by the ash.

The first exploitation experience of the CFB boilers allows to state (confirm) significantly better situation in matter of fouling and high-temperature corrosion.

From the environmental safety viewpoint, another important ash parameter is the sulphide sulphur content. In the laboratory-tested Eesti Power Plant's FB boiler ash samples the sulphide sulphur content fluctuated at 0-0.28%, being lower in finer ash fractions (0-0.17%). It can be assumed that in this context the ash from FB boilers does not differ from that from PF boilers.

A separate positive feature of FB boilers is the considerable decrease of the CO₂ amount emitted into the air. One well-known and persistent negative aspect of oil shale has been the large amount of CO₂ atmospheric emissions due to the fact that the CO₂ from the combustion of the fuel's organic part is in the case of oil shale supplemented with the CO₂ from the decomposition of carbonates in the fuel's mineral part. The amount of CO₂ emitted into the air from FB boilers is decreased due to two reasons. Firstly, the CO₂ amount decrease is based on the smaller extent of carbonates decomposition in such boilers due to low furnace temperatures. Secondly, the smaller extent of carbonates decomposition and large extent of sulphur binding cause, in their own turn, an increase of the amount of heat from the fuel fed into the boiler, which is why less fuel is needed for the same steam amount production.

To compare the CO₂ emissions from FB boilers with those from PF boilers at the same net thermal loads, Table 2 contains calculation data based on the information obtained by Elektrowatt-EKONO during the tests at block 8 of Eesti Power Plant – amounts of CO₂ emissions for FB boilers. The amounts of CO₂ emissions for PF boilers, as quoted in the table, were calculated on the basis of the same fuel data and net capacities. The boiler efficiency factor is in this case the average figure for TP-101 boilers in 2002 (82.28%) [13], extent of carbonates decomposition – 97% and extent of sulphur binding – 80%.

As the presented data calculated on the basis of the information obtained in the course of the boiler tests shows, at the same loads the amount of CO₂ emissions from CFB boilers is 15-18% less of the amount emitted from PF boilers.

The decrease of emissions while using the CFB technology given in Table 3.

Table 2. Comparison of amounts of CO₂ emitted from CFB and PF boilers

Parameter	Sign	Meas. unit	Test 1		Test 2		Test 3	
			Boiler 1	Boiler 2	Boiler 1	Boiler 2	Boiler 1	Boiler 2
Boiler net capacity	Q _{NET}	MW	251.4	249.2	251.7	246.4	243.9	243.1
CFB boiler								
Fuel flow	m	kg/s	33.72	32.35	31.29	34.05	30.21	31.24
Boiler efficiency	η	%	93.94	94.84	94.90	93.29	93.55	93.74
Lower heating value	LHV	MJ/kg	7.86	8.00	8.40	7.68	8.54	8.22
Fuel carbonate CO ₂ content	(CO ₂) _M ^r	%	18.36	18.09	18.09	18.75	17.38	17.98
Extent of carbonates decomposition in boiler		%	72.5	71.1	70.6	73.1	77.6	71.6
Amount of CO ₂ emitted with flue gas	G _{CO2-CFB}	t/h	103.1	99.8	99.9	102.9	98.2	98.3
PF boiler								
Fuel flow	m	kg/s	38.55	37.55	36.12	38.67	34.42	35.64
Boiler efficiency	η	%	82.28	82.28	82.28	82.28	82.28	82.28
Extent of carbonates decomposition in boiler		%	97.00	97.00	97.00	97.00	97.00	97.00
Amount of CO ₂ emitted with flue gas	G _{CO2-PF}	t/h	124.1	122.1	121.5	123.1	116.0	118.0
Amount of CO ₂ emitted from FB boilers compared to that emitted from PF boilers		%	83.1	81.7	82.2	83.6	84.6	83.3

Table 3. Comparison of renovated energy unit with CFB boilers to the old units with PF boilers

Parameter	Meas. unit	Renovated unit	Old unit	Difference
Block capacity	MW _e	215	about 180	Increasing more as 19%
Net plant heat rate	kJ/kWh	9 200-9 500 [13]	11 700-12 000	Decreasing over 20%
Sulphur dioxide emissions SO ₂	mg/Nm ³	<20	2000	Decreasing over 100 times
Nitrogen dioxide emissions, NO _x	mg/Nm ³	<160	300	Decreasing about 2 times
Carbon dioxide emissions, CO ₂	t/GWh	920-950	1190-1225	Decreasing over 20%
Fly ash emission	mg/Nm ³	25-30	100	Decreasing 3-4 times

From the viewpoint of the environmental hazard of fuel ashes, there is another parameter that is of interest – content of hazardous organic compounds in ash. The analysis of different ash fractions from FB boilers aimed at determining the amount of such compounds in them was con

ducted at the Institute of Chemical and Biological Physics. As the initial analysis results of the ash samples indicated, the content of hazardous organic compounds, especially polycyclic aromatic hydrocarbons, in the ash from FB boilers is lower than in the ash of PF boilers.

Full scale emission measurement campaign, provided for estimation of the environmental impact of Estonian oil shale combustion at new CFB units was carried through in spring of 2006. It proved, that conversion to oil shale CFB firing instead of PF resulted beside reduction of common flue gas components also almost zero emissions of dioxins and furans and polycyclic aromatic hydrocarbons.

Thanks to the new efficient electrostatic precipitators (content of solid particles in flue gases below 30 mg/Nm³) heavy metal emissions remain very low also.

SUMMARY

Below is a brief overview of the most important aspects of the implementation of the FB technology at Eesti Energia Ltd:

- The extensive studies and oil shale test combustions at the boiler manufacturing companies in 1993-1998, it was discovered that the best available combustion technology for Estonian oil shale is atmospheric CFB technology.
- The intensive fouling and the high-temperature corrosion and wear of boiler heating surfaces taking place in PF boilers had not appeared in CFB boilers.
- The level of the emissions from the CFB units has been substantially lower than the strict emissions norms stipulated by the European environmental regulations. It should be noted that the sulphur dioxide emissions level is actually over 10 times lower than the enforced boundary limit of 200 mg/Nm³ – it is only <20 mg/Nm³. The level of nitrogen dioxides <160 mg/Nm³, is also lower than the boundary limit 200 mg/Nm³.
- The operation experience of CFB energy units had indicated that the new boilers excellently function on oil shale: the renovated energy unit easily achieves the nominal load of 215 MW_e. Eesti Energia Ltd now has at its disposal 2x215 MW_e efficient and environmentally-friendly productive capacities.
- The introduction of the low-temperature FB technology for Estonian oil shale has been completely justified and the acquired positive experience serves as a solid foundation for ensuring the sustainability and competitiveness of the oil shale energy industry.
- In the course of the implementation, the staff of Eesti Energia Ltd acquired excellent experience of supervising and carrying out such a large project – a good premise for renovating the next energy units.

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