

## SHORT-TERM TESTS ON FIRING OIL SHALE FUEL APPLYING LOW-TEMPERATURE VORTEX TECHNOLOGY

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*The present paper provides experimental data from short-term, full-scale experiments of a high-pressure pulverized firing (PF) boiler, TP-67, firing oil shale after a retrofit to use vortex combustion (VC) technology. The essence of VC technology consists of the generation, at a lower part of the furnace, of a circulatory motion of gas relative to the horizontal axis (horizontal vortex) by rearranging the geometry of the combustion air injection and the fuel feeding into the combustion chamber. The tests were conducted at three boiler loads: 50% (160 t/h), 75% (240 t/h) and 100% (320 t/h). During the experiments, fuel samples of air-solids in the conduit and samples of bottom ash and fly ash 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 and second fields, were taken from both the left and the right sides of the boiler. The gas analysis was performed at the ESP exit. It was attempted to measure temperature distribution in the combustion chamber. Temperature measurements in the furnace using an infrared thermometer showed that the maximum temperature did not exceed 1150 °C, and there was slight temperature nonuniformity across the combustion chamber. During the tests, the ash distribution at different boiler ash discharge ports was obtained. Analysis of the bottom ash chemical composition showed a considerable increase in the amount of unburned carbon and marcasite  $S_p$ . The retrofit of the boiler to use VC technology did not result in a reduction in the amount of  $SO_2$  emissions, indicating an even weaker process of binding sulphur oxides in the furnace as compared to PF.*

### Introduction

At the present time, more than 90% of the electricity production in Estonia is generated by burning oil shale fuel, and most of this electricity generation is

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based on pulverized firing (PF) technology. Some of the characteristics that are attributed to this technology, including 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 ground fuel, also significantly characterize the thermal conversion of the mineral part of oil shale, which will eventually lead to intense deposition formation and corrosion of the boiler heat transfer surfaces. Generally, it is possible to decrease the deposition formation and the rate of corrosion of the heat transfer surfaces, therefore improvement of the fuel efficiency, by decreasing the temperature in the combustion chamber, increasing the coarse-ground particle fraction of the fuel and preventing the formation of reducing atmosphere zones in the furnace.

One concept pertaining to combustion technology that makes it possible to decrease the temperatures in the combustion chamber is the low-temperature vortex combustion (VC) method, the basic principles of which were first developed by Leningrad Polytechnical Institute in collaboration with NPO CKTI (formerly Central Boiler and Turbine Institution) [1]. The essence of this combustion technology consists of the generation, at a lower part of the furnace, of a circulatory motion of the gas relative to the horizontal axis (horizontal vortex) by rearranging the geometry of the combustion air injection and the fuel feeding into the combustion chamber. This process allows for a reduction in the maximum temperature level within the furnace, which equalizes the heat flux distribution and increases the heat absorption. Due to multiple circulations of the particles in the furnace, the coarse-ground particle fraction of the fuel could be fed.

The first full-scale experiments on vortex combustion technology using oil shale as fuel were conducted in the early 70s on the medium-pressure boiler BKZ-75-39F at the Ahtme Thermal Power Plant (Estonia) and Slantsy Power Plant (Russia). The main findings have been previously described [1–10]. During the reconstruction of the boilers, the combustion air injection direction of the frontal mounted burners was changed, and the nozzles of the lower forced draft were mounted within the opening of the combustion chamber throat. The grinding fineness of the fuel was increased from  $R_{90} = 16.5\text{--}28$  to  $R_{90} = 48\text{--}60$ . To maintain the temperature in the furnace below 1180 °C, the exceeding of which leads to an intensification of the slagging processes and the formation of tightly bound deposits, a radiant super heater platens was installed in the lower part of the combustion chamber. To reduce the erosive wear of the economizer (ECO) in the flue gas pass after the convective super heater, a specially designed high-temperature ash collector was mounted. The arrangements made during the reconstruction helped to increase the maximum nominal steam capacity from 16.7–18.0 kg/s up to 21.0–21.7 kg/s and to increase the boiler's thermal efficiency (gross) from 86.0–86.5% up to 88.0–90.8% due to the decrease of the flue gas temperature at the boiler outlet. Simultaneously, increases in losses due to enthalpy and unburned carbon in the bottom ash were observed; they were caused by

the increased amount of ash particles captured in the furnace (up to 50%) when using the coarse-ground particle fraction of the fuel. The considerable increase in the content of sulphur, mainly marcasite, in the bottom ash was found to be caused by the occurrence of the reducing atmosphere zones in the furnace.

As described previously [10], a comparative analysis of the chemical composition of the fly ash that was obtained using the different fuel combustion technologies like PF and VC showed that the content of the ash components that are most prone to sulphation, such CaO and MgO, are nearly identical in the fine particle fraction and in the coarse particle fraction. When using VC for firing coarse-ground fuel, no noticeable increase in the relative K<sub>2</sub>O content in the fine particle fraction relative to the content in the coarse fraction was observed when the median diameter  $\Delta_s$  of the fly ash was increased. The ratio of the K<sub>2</sub>O in case of the vortex combustion was approximately 2.2 at  $\Delta_s = 51 \mu\text{m}$ , whereas for PF it reached a value of approximately 3.5–4.1  $\mu\text{m}$  as  $\Delta_s$  increased up to 26–28  $\mu\text{m}$ . The considerable increase in the chlorine content (Cl = 2.56–3.82%) in the fine fraction of the fly ash using VC was found to be several times higher than the corresponding content (Cl = 0.20–0.50%) [2] using PF. In the opinion of the authors, this difference was caused by changing the atmosphere of the combustion chamber (the occurrence of the reducing atmosphere zones).

Subsequently in 1981, the reconstruction of the high-pressure boiler TP-17 at Balti Power Plant to use VC technology was performed [1]. Experiments showed that during the entire period of the operation of the boiler before the planned overhaul, the gas temperatures along the flue gas path, as well as the steam temperatures, remained stable without the application of heat transfer surface cleaning devices in the furnace and super heater. Intensive deposit formation on the heating surfaces could be explained as follows [1]. It is known that the chemical composition of the ash that forms during oil shale combustion is different for the various ash particle fractional groups; the most chemically active components are contained within the finest ash particle fraction. As VC technology uses coarse-ground fuel and there is strong relationship between fractional compositions of the fuel and the ash formed, there is a decrease in the fraction of particles that contain chemically active components and an increase in the fraction of inert particles that have a destructive effect on deposit formation.

Simultaneously, the coarse particle fraction of the ash, the increased flue gas velocity that occurs with formation along the flue gas pass cross-sections with a highly nonuniform flow and the distribution of the fly-ash particles have significantly intensified the erosive wear process. For example, in the case of the medium-pressure boiler BKZ-75-39F, after 350 h of continuous operation at a mean boiler load of 20.5 kg/s, a magnitude of wear of the economizer tubes of approximately 0.4–0.6 mm was observed.

The present paper provides experimental data from a short-term, full-scale test of a high-pressure boiler, TP-67, firing oil shale after reconstruc-

tion to use VC technology. The implementation of VC technology on high-pressure boiler TP-67 was performed by Polytechenergo Ltd during 2008–2010.

## Experimental

The full-scale experiments of the present investigation were carried out on a high-pressure boiler, TP-67, at the Balti Power Plant, which is located in eastern Estonia [11]. The boiler is of a Taganrog boiler-making works (“Krasny Kotelshchik”) design and has been in operation since the 60s. The main parameters of the boiler are as follows: boiler load (live steam) 280 t/h, live steam pressure and temperature – 13.8 MPa and 515 °C, respectively.

The lower heating value (LHV) of oil shale used in the thermal experiments was at approximately 10.77 MJ/kg; the studied oil shale characteristics on an as-received basis are provided in Table 1.

The flue gas analysis performed by the plant personnel from the gas laboratory shortly before the transfer of the boiler to use VC technology showed that the normalized contents (reduced to O<sub>2</sub> = 6%) of the SO<sub>2</sub> and NO<sub>x</sub> for the dry gases were approximately 2097 mg/Nm<sup>3</sup> and 338 mg/Nm<sup>3</sup>, respectively.

In the original design, the boiler (see Fig. 1) was equipped with vortex burners that are mounted on the frontal panel in two different row arrangements, with four burners on each row. The fuel is ground by four MMT-1500-2510-735 hammer mills, which have a compact separator of the pulverized fuel at their outlet. In addition to a combustion chamber, the boiler has two vertical flue gas passes in the first downflow, in which the hanging platen super heaters having longitudinal flows of gas are installed. The second rising flue gas pass contains the economizer and the air

Table 1. Studied oil shale characteristics on an “as-received” basis

Parameter	Value, wt%
Carbon, C <sup>r</sup>	25.87
Hydrogen, H <sup>r</sup>	3.34
Oxygen, O <sup>r</sup>	4.76
Nitrogen, N <sup>r</sup>	0.05
Organic sulphur, S <sub>o</sub> <sup>r</sup>	0.3
Pyritic sulphur, marcasite, S <sub>p</sub> <sup>r</sup>	0.91
Sulphate sulphur, S <sub>o</sub> <sup>r</sup>	0.09
Chlorine, Cl	0.14
Mineral carbon dioxide, CO <sub>2</sub> <sup>r</sup>	12.9
Corrected ash content, A <sub>co</sub> <sup>r</sup>	36.28
Crystal water, W <sup>r</sup>	0.56
Moisture, W <sup>r</sup>	14.9
Total*	100

\* – does not contain sulphate sulphur because it is included in the corrected ash content

preheater. Behind the air preheater, the flue gas pass splits into two channels (channel A, located on the left side of the boiler front, and channel B, located on the right side) that connect the tail of the boiler with two electrostatic precipitators (ESP), the left ESP and the right ESP relative to the front of the boiler. Each ESP is connected to the induced draft fan by two channels (left and right channels, similarly denoted relative to the front of the boiler). A more detailed description, including the design features and thermal characteristics of the considered boiler can be found in [2].

For generation of low-temperature horizontal vortex motion in the combustion chamber, a set of modifications were made. The modifications included replacing the vortex burners that were located at the lower row with direct-flow burners with a downward slope. The opening of the combustion chamber throat along the entire width of the lower forced draft was performed by mounting two-stage deflection-nozzle devices. With the aim of obtaining a coarse-ground fraction of fuel feeding into the lower row of burners, the hammer-mill separator was modified. The forced draft fan capacity was increased by building up the fan wheel blades and installing a more powerful motor.

The tests were conducted at three boiler loads: 50% (160 t/h), 75% (240 t/h) and 100% (320 t/h). The sampling of pulverized fuel from the air-solids conduits supplying fuel to the replaced direct-flow burners of the lower burner row (with a modified solid separator) and to the original vortex burners of the upper row was performed to determine the particle size distribution. The sampling was performed by means of a VTI design sampling device with a cobra-type probe head with an inner diameter of 46 mm. The probe was equipped with a manual system allowing the equalization of the velocities in the channel of the probe and in the pulverized fuel conduit during the sampling (isokinetic sampling). The fuel samples were taken over the cross section of the air-solids conduit at ten points that were derived by dividing the conduit's cross-sectional area into concentric, equal area rings and a central circle.

During the experiments, samples of bottom ash and fly ash from the inertia dust collectors after SH and ECO, as well as from the ESP of the first and second fields, were taken from both the left and the right sides of the boiler. The ash sampling location is shown in Fig. 1. In addition, the isokinetic fly ash samples from the flue gas pass after the AP and before the ESP were obtained. To determine the modified boiler ash balance, the ash mass flow rates in the ash discharge ports were received experimentally. The ash mass flow of the dust collectors located under the SH and ECO were determined by a slurry method that consisted of measuring the time required to fill the calibrated volume by slurry and in the subsequent determination of the slurry mass. The mass flow of the fly ash entering into the ESP was obtained by measuring the fly ash content in the flue gas pass before the ESP; the measurements were performed using an Emes 3866 (VTT-Energy Ltd) according to Finnish standard SFS 3866. The bottom ash flow mass was

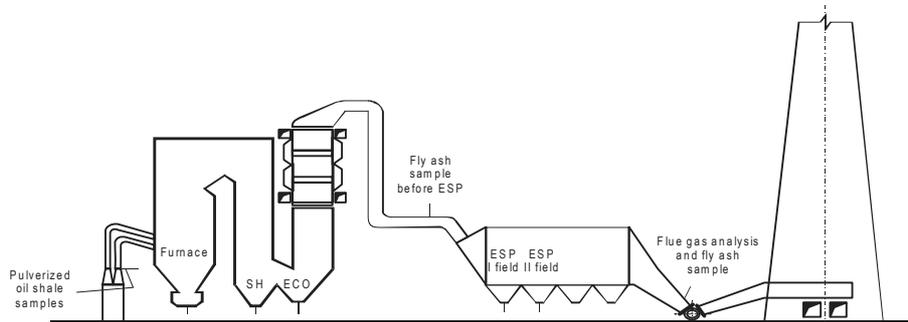


Fig. 1. Sectional side view of the Boiler TP-67.

calculated as the difference between the total ash mass flow entering into the boiler with fuel, which was determined through the indirect heat balance of the boiler, and the total fly ash mass flow.

The gas analysis was performed both in the right flue gas duct at the left ESP exit and in the left flue gas duct at the right ESP exit using the F-TIR type gas analyzer (Gasmeter DX-4000).

During the tests, an attempt was made to measure the temperature distribution in the combustion chamber. The measurements were performed by an infrared thermometer (M90L, Mikroninstrument) operating in the  $\text{CO}_2$  absorption band. Prior to these tests, parallel measurements of the flame temperature in the furnace of a boiler that was firing oil shale made with this infrared thermometer and a suction pyrometer have shown that the spectral flame emissivity in the  $\text{CO}_2$  absorption band is close to unity.

## Results and discussion

### Temperature distribution in the furnace

The measurements of the flame temperature in the furnace were performed at five different cross-sections along the height of the boiler (see Figs. 2-4) in the following locations: at 8 m on the left and right sides of the furnace, at 12 m in the left rear corner, at 16 m on the rear wall, at 20 m on the left and right sides and on the center of the frontal wall and at 24 m on the left part of the frontal wall.

The first measurements at full load have shown that the gas temperature in the left upper part of the furnace volume was significantly higher than the corresponding values for other measuring points. The maximum temperature obtained was  $1370\text{ }^\circ\text{C}$  and varied within the range from  $1270\text{--}1370\text{ }^\circ\text{C}$ . A high nonuniformity of the temperature field along the furnace width was observed. In subsequent experiments, after the reconstruction team performed some additional boiler adjustments, the maximum temperature was decreased and no longer exceeded  $1150\text{ }^\circ\text{C}$ , and the temperature distribution along the furnace cross section was more uniform.

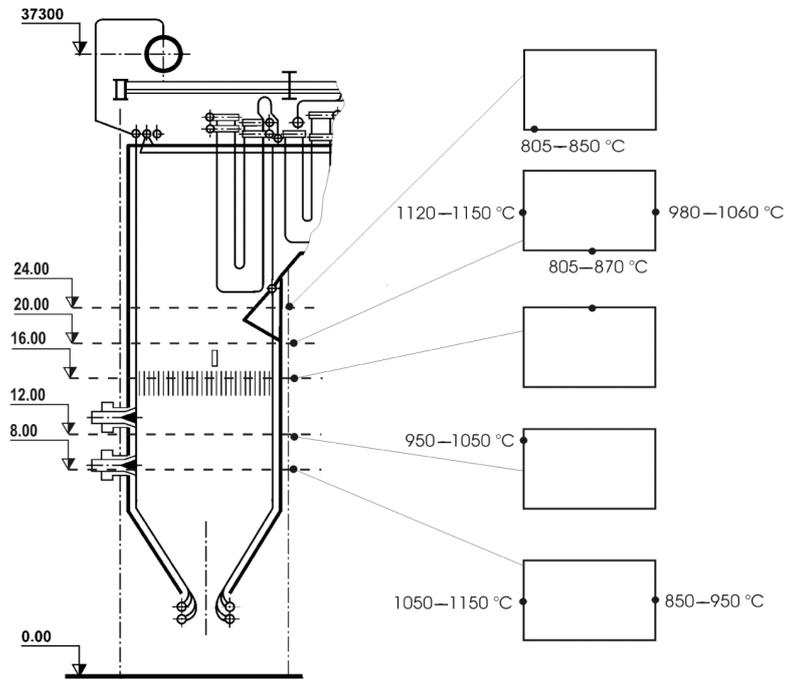


Fig. 2. Temperature distribution in the furnace at 100% boiler load.

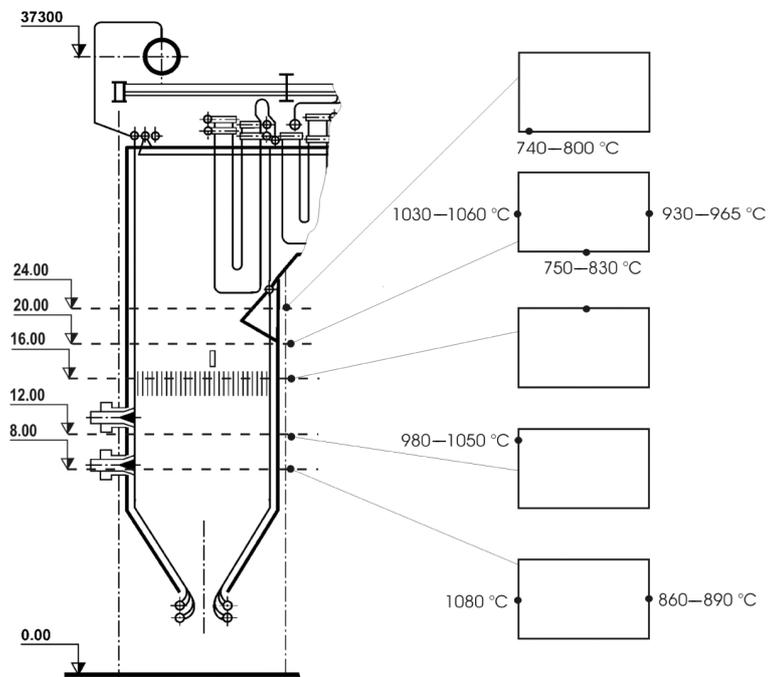


Fig. 3. Temperature distribution in the furnace at 75% boiler load.

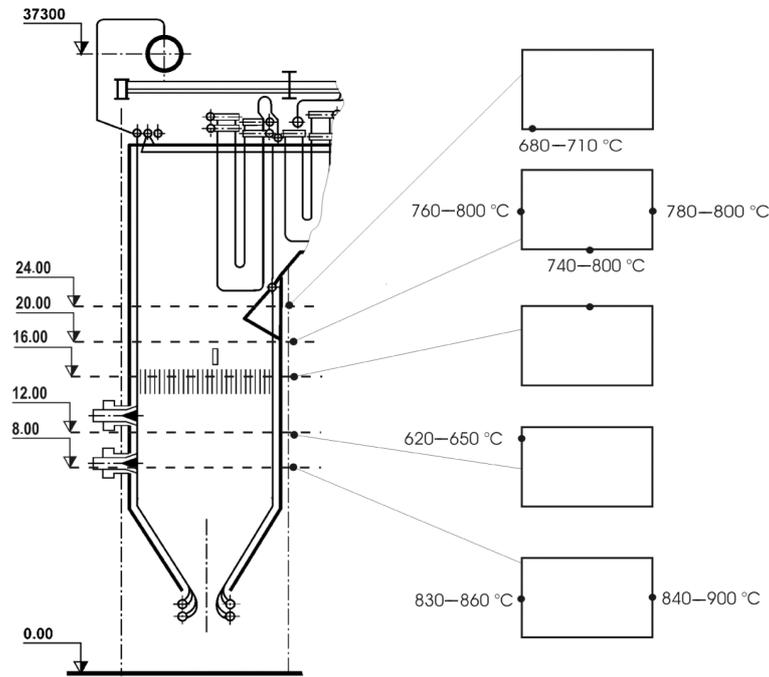


Fig. 4. Temperature distribution in the furnace at 50% boiler load.

### Size distribution analysis of fuel/ash and ash mass flow balance

The results of a comparative size distribution analysis of the pulverized fuel after both a modified and an unmodified separator are presented in Table 2. It is clear that there are significant differences in the fuel fractional composition. The median particle diameter of the fuel entering the lower row burners increased by 2.5-fold, and the percentage residue  $R_{200}$  on the sieve with a grid spacing of  $200\ \mu\text{m}$  increased by approximately 1.7 times, indicating increasing percentages of coarse fuel particles as compared to finer particles.

Firing coarse-ground fuel resulted in changing the fractional composition of the bottom and fly ashes (see Table 3). As compared to the PF technology at a full boiler load (here, as an example, the ash particle fractional composition of the PF boiler TP-101 is used), it can be seen from Table 3 that significant ash particle coarsening occurs in different boiler locations.

Table 2. Fractional composition at 100% boiler load

Parameter	Modified separator	Unmodified separator
Median particle diameter $\Delta_m$ , $\mu\text{m}$	90–200	35–50
Sieve residue $R_{90}$ , %	46–57	32–42
Sieve residue $R_{200}$ , %	34–46	19–29

**Table 3. Fractional composition of the ash at different ash discharge ports at 100% boiler load**

Parameter	Bottom ash	Super heater	Economizer	ESP 1 field
Median ash particle diameter $\Delta_m$ , $\mu\text{m}$	600–1500	300–380	290–320	25–45*
Sieve residue $R_{90}$ , %	~95*	~95*		15–30
Sieve residue $R_{200}$ , %	80–90	70–80	75–85	3–6
Median diameter (TP-101 boiler) $\Delta_m$ , $\mu\text{m}$	200–300	~180	~95	10–12
Sieve residue (TP-101 boiler) $R_{90}$ , %	~88	~80	~55	
Sieve residue (TP-101 boiler) $R_{200}$ , %	~56	~45	~15	

\* – values are obtained by extrapolating

More than a two-fold increase in the median ash particle diameter  $\Delta_m$  was observed. The residue  $R_{8000}$  of bottom ash on the sieve with an aperture of 8000  $\mu\text{m}$  varied within the range from 0.5–4%, depending upon on which side of the boiler furnace the ash sample was obtained from. A relative increase in the coarse fraction and a decrease in the fine fraction of the ash has likely become one of the main factors resulting in the reduction of the rate of deposit formation on heating surfaces. This change has allowed for an increase in the boiler capacity from 290 t/h to 320 t/h. The coarse particle fraction increase with the simultaneous increase of the flue gas pass velocity due to both the increase in the boiler load and the change in the combustion air regime can cause the intensification of the erosive wear process on the heating surfaces; the parts that are most susceptible to wear are the tubes of the ECO.

When reducing the boiler load to the minimum (50% of rated load, 160 t/h), an increase in the median particles diameter  $\Delta_m$  of the bottom ash and the first fields ESP fly ash was observed (see Table 4). In contrast, a slight decrease in the median diameter of the fly ashes collected from the SH and ECO ducts was found.

The results of the ash balance of the considered reconstructed boiler under a full load (100%, 320 t/h) are depicted in Fig. 5. From Fig. 5, it can be seen that in spite of the coarsening of the ash particles, the share of the ash streams captured in the furnace (bottom ash) was smaller than expected compared to the previously conducted experiments on medium-pressure boilers that were described in Introduction section. The bottom ash stream was found to be approximately 23% of the total ash flow rate. In the absence

**Table 4. Fractional composition of the ash at different ash discharge ports at 50% boiler load**

Parameter	Bottom ash	Super heater	Economizer	ESP 1 field
Median diameter $\Delta_m$ , $\mu\text{m}$	900–1500	220–270	280–300	90–120
Sieve residue $R_{90}$ , %	~95*	~94*		52–67
Sieve residue $R_{200}$ , %	95–97	60–67	70–78	18–20

\* – values are obtained by extrapolating

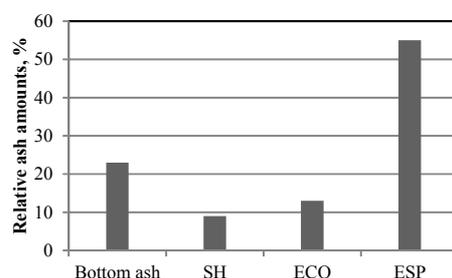


Fig. 5. Ash mass flow rate distribution at different ash discharge ports at 100 % boiler load.

of reliable data in the literature concerning the ash stream distribution at different ash discharge locations of the studied boiler using PF technology, it could be stated on the basis of experimental data that there was a slight decrease in the bottom ash flow rate after the retrofit of the boiler to use VC technology. An even smaller amount of total ash was discharged in the inertia ash collectors located in the SH and ECO ducts: 9% and 13%, respectively. Therefore, the main part of the total ash, approximately 55%, was entrained by the flue gas stream and collected at the ESP.

During the present experiments, an attempt was made to obtain ash amount distributions at different boiler locations at the boiler minimum load (50%, 160 t/h of live steam). Due to inaccuracies in determining the fly ash content entering the ESP at increased gas velocities, these data are not presented here. However, according to these data, an increase was observed in the amounts of bottom ash and fly ash discharged at inertia ash collectors located in the SH and ECO ducts.

### Chemical composition of the ash

The results of the chemical analysis of the ash at different discharge locations at a boiler load of 320 t/h (100%) and 160 t/h (50%) are summarized in Tables 5 and 6. Analyzing the chemical composition of the bottom ash when firing oil shale by applying VC technology shows a considerable increase in the amount of unburned carbon, which was caused by the separation of the coarser, unburned particles through the furnace throat opening. A significant increase in the amount of marcasite sulphur  $S_p$  in the bottom ash, most probably due to the occurrence of reducing atmosphere zones in combustion chamber, was also observed. The simultaneous maintenance of a lower temperature in the furnace with the feeding of coarse-ground fuel resulted in a lower degree of decomposition of carbonate minerals in the furnace as compared to the PF technology. At a full boiler load, the extent of the carbonate mineral decomposition was approximately  $k_{CO_2} = 0.84$ .

From Tables 5 and 6, it can be seen that the content of components causing sulphation, such as CaO and Na<sub>2</sub>O, in the finer fraction of the ash

Table 5. Chemical composition of the ash at different ash discharge ports at 100% boiler load

Parameter	Bottom ash, right side, wt%	Bottom ash, left side, wt%	Super heater, right side, wt%	Super heater, left side, wt%	Economizer, right side, wt%	Economizer, left side, wt%	ESP 1 field, right side, wt%	ESP 1 field, left side, wt%	ESP 2 field, right side, wt%	ESP 2 field, left side, wt%
CO <sub>2</sub>	21.5–26.5	19.3–14.1	3.6–4.7	3.3–4.3	4.7	2.5–4.0	2.6–2.7	2.0–2.5	2.7	2.5
C <sub>el</sub>	9.59–10.61	8.00–7.13	0.93–1.23	0.73–1.11	1.21	0.57–1.07	0.64–0.60	0.43–0.45	0.66	0.48
S <sub>el</sub>	0.78–0.92	0.85–0.78	1.40–1.59	1.56–1.94	1.50	1.49–1.48	2.84–2.35	2.65–2.45	2.47	3.16
SO <sub>3</sub> total	1.95–2.30	2.13–1.95	3.43–3.63	3.48–3.73	3.75	3.73–3.70	7.1–5.88	6.63–6.13	6.18	7.90
S <sub>s</sub>	0.46–0.39	0.52–0.51	1.40–1.56	1.55–1.94	1.52	1.49–1.60	2.75–2.32	2.80–2.42	2.44	2.90
S <sub>p</sub>	0.32–0.53	0.33–0.27	0.03	0.01	–	–	0.09–0.03	0.03	0.03	0.26
SiO <sub>2</sub>	14.64–11.22	18.20–18.37	23.72–22.4	24.4–23.0	20.72	22.52–22.17	30.75–29.25	25.77–27.81	24.84	26.58
Fe <sub>2</sub> O <sub>3</sub>	3.55–3.62	2.49–3.81	5.15–4.56	5.01–4.51	4.56	4.70–4.69	4.47–4.79	4.20–4.66	4.42	4.07
Al <sub>2</sub> O <sub>3</sub>	4.88–10.40	5.61–4.56	6.48–5.87	6.72–5.77	4.12	4.66–5.12	11.82–7.44	7.31–7.76	5.48	6.56
CaO	52.45–50.32	45.68–54.04	53.21–54.06	51.66–50.79	55.82	55.80–50.89	48.97–43.08	49.32–44.21	50.23	46.07
CaO <sub>free</sub>	5.57–6.06	8.56–6.67	24.49–24.22	25.08	–	–	19.45–14.62	18.12–15.53	–	–
MgO	2.56–3.86	1.79–3.22	1.51–2.66	3.42–4.11	2.68	3.06–6.72	0.52–4.62	3.06–4.82	2.49	2.09
K <sub>2</sub> O	0.16–0.14	0.16–0.14	2.08–2.11	2.10–3.64	1.64	1.61–1.8	0.85–3.20	3.03–3.07	2.41	3.27
Na <sub>2</sub> O	1.27–1.10	1.41–1.72	0.18–0.20	0.18–2.28	0.18	0.16–0.16	0.21–0.20	0.22–0.21	0.18	0.23
Heat loss	25.1–30.5	23.6–20.3	3.8–4.8	3.3–4.7	4.9	2.4–4.3	2.9–2.6	2.1–2.1	2.8	2.3

Table 6. Chemical composition of the ash at different ash discharge ports at 50% boiler load

Parameter	Bottom ash, right side, wt%	Bottom ash, left side, wt%	Super heater, right side, wt%	Super heater, left side, wt%	Economizer, right side, wt%	Economizer, left side, wt%	ESP 1 field, right side, wt%	ESP 1 field, left side, wt%	ESP 2 field, right side, wt%	ESP 2 field, left side, wt%
CO <sub>2</sub>	31.4	30.0	15.1	13.3	15.1	13.4	7.6	6.9	4.5	4.2
C <sub>el</sub>	17.73	11.99	4.04	3.65	4.17	3.61	2.04	1.81	1.19	1.00
S <sub>el</sub>	1.17	1.17	1.59	2.10	2.17	1.97	2.59	2.45	2.84	3.0
SO <sub>3total</sub>	2.93	2.93	3.98	5.26	5.43	4.93	6.48	6.13	7.10	7.50
S <sub>s</sub>	0.33	0.50	1.59	2.15	2.12	2.00	2.48	2.40	2.81	2.94
S <sub>p</sub>	0.84	0.67	–	–	0.05	–	0.11	0.05	0.03	0.06
SiO <sub>2</sub>	7.95	8.99	14.94	17.23	13.13	13.83	20.55	19.77	27.68	27.61
Fe <sub>2</sub> O <sub>3</sub>		2.42	3.81	3.97	3.89	3.37	4.24	2.13	4.47	4.63
Al <sub>2</sub> O <sub>3</sub>		5.47	4.56	4.30	3.66	7.18	4.23	13.09	5.56	5.48
CaO	47.0	50.54	49.86	52.13	50.22	54.11	50.47	63.49	43.38	42.77
CaO <sub>free</sub>	2.0	5.67	20.92	23.9				23.69		
MgO	2.49	3.70	2.00	1.34	4.79	2.59	3.37	4.43	2.73	2.78
K <sub>2</sub> O	0.85	0.92	1.89	0.13	1.37	1.19	1.55	1.92	2.64	2.91
Na <sub>2</sub> O	0.19	0.12	0.15	0.13	0.13	0.15	0.13	0.19	0.20	0.21
Heat loss	41.3	34.0	14.7	13.6	15.5	13.3	7.6	6.8	4.6	4.0

( $\Delta_m = 25\text{--}40\ \mu\text{m}$ , fly ash obtained from the first field of the ESP in the case of VC and from the cyclone of boiler TP-101 in the case of PF) is approximately the same for the VC and PF technologies. However, the content of MgO was found to be somewhat lower (on average 50%), and the content of K<sub>2</sub>O was found to be higher (on average 50%) for the VC compared to the PF technology.

### Flue gas analysis

The results of the flue gas analysis performed behind the ESP before the induction of a draft fan in two ducts at different boiler loads are presented in Table 7. It can be seen that the retrofit of the boiler to use VC technology did not result in a reduction of SO<sub>2</sub> emissions, indicating an even weaker process of binding sulphur oxides in this furnace compared to the PF. This lack could partially be explained by the following reasons. As the Estonian oil shale in nature is heterogeneous fuel, during the process of oil shale pulverizing and separating, the redistribution of the fuel components by particle fractions occurs: the sulphur (most forms) locates within the finer particle fraction, whereas molecules participating in the process of binding sulphur oxides, i.e., the free lime CaO<sub>free</sub>, locate within coarser particle fraction. During the fuel particle separation process that occurs in a vortex combustion chamber, the lighter particles, containing mostly the organic components of fuel (organic sulphur in particular), and the finer particles, consisting of the sandy clay part of the fuel (marcasite in particular), are entrained by the gas stream into the direct-flow jet, bypassing the recirculation vortex zone that forms in the lower part of the furnace. As a result, the CaO content decreases in just that zone where the modification of sulphur oxides occurs during combustion. Additionally, the reduction in sulphur capture that occurs by implementing VC is obviously caused by the coarsening of the ash particles, which then have a smaller specific surface area compared to the ash that forms during PF. The specific surface area

Table 7. Emissions of SO<sub>2</sub>, NO<sub>x</sub> and CO at different boiler loads

Experiment number	Flue duct	Boiler load, t/h	NO <sub>x</sub> , mg/Nm <sup>3</sup> (6% O <sub>2</sub> )	SO <sub>2</sub> , mg/Nm <sup>3</sup> (6% O <sub>2</sub> )	CO, mg/Nm <sup>3</sup> (6% O <sub>2</sub> )
Exp 1	ESP A, right channel	160	312	3585	830
Exp 2	ESP A, right channel	160	455	1707	40.1
Exp 3	ESP A, right channel	160	362	2225	25.5
Exp 4	ESP B, left channel	160	391	1971	26.2
Exp 5	ESP B, left channel	240	384	2314	13.5
Exp 6	ESP A, right channel	240	372	2490	9.9
Exp 7	ESP B, left channel	320	327	3164	0.0
Exp 8	ESP A, right channel	320	336	2715	1.1
Exp 9	ESP A, right channel	320	334	3083	0.2
Exp 10	ESP B, left channel	320	302	3344	0.3

decrease inevitably leads to a decrease in the intensity of the chemical reaction between CaO and SO<sub>2</sub>.

The results show that with increasing boiler loads, the SO<sub>2</sub> content was increased and varied within the range from 2715–3344 mg/Nm<sup>3</sup> (reduced to 6% of the O<sub>2</sub>). The content of the nitrogen oxides NO<sub>x</sub> for both combustion technologies at a full boiler load was at approximately the same level. As the boiler load decreases, the content of the NO<sub>x</sub> increases.

## Conclusions

The present paper provides experimental data from short-term, full-scale experiments after the retrofit of a high-pressure PF boiler TP-67 operating on oil shale, to use VC technology.

The retrofit of the boiler to use VC technology has enabled an increase in the boiler maximum continuous output rate up to 320 t/h.

The temperature measurements, which were performed using an infrared thermometer, show that the maximum temperature across the furnace did not exceed 1150 °C (on the left side of the boiler). Slight temperature nonuniformity across the combustion chamber was observed, and the temperature difference between the left and right sides did not exceed 100–150 °C.

The firing the coarse-ground fuel resulted in the changing of the fractional composition of the bottom and fly ash, and more than a two-fold increase in the median ash particles diameter  $\Delta_m$  was observed. The residue R<sub>8000</sub> of bottom ash on the sieve with an aperture of 8000  $\mu\text{m}$  varied within the range of 0.5–4%, depending on which side of the boiler the ash sample was obtained from. When reducing the boiler load to the minimum (50% of rated load, 160 t/h), an increase in the median particle diameter  $\Delta_m$  of the bottom ash and the first fields ESP fly ash was observed. In contrast, a slight decrease in the median diameter of the fly ash collected from the SH and ECO ducts was also found.

During the tests, the distribution of the amount of ash at different boiler locations was experimentally obtained. The bottom ash stream was found to be approximately 23% of the total ash flow rate. Smaller amounts of total ash were discharged in inertia ash collectors located in the SH and ECO ducts (9% and 13%, respectively). Therefore, the main part of the total ash, approximately 55%, was entrained by the flue gas stream and collected at the ESP.

Analysis of the bottom ash chemical composition has shown the considerable increase in the amounts of unburned carbon and marcasite S<sub>p</sub>. At a full boiler load, the extent of carbonate mineral decomposition in the furnace was approximately  $k_{\text{CO}_2} = 0.84$ .

The retrofit of the boiler to use VC technology did not result in the reduction of SO<sub>2</sub> emissions, indicating an even weaker process of binding sulphur oxides in the furnace compared to the PF technology. The SO<sub>2</sub>

content normalized to  $O_2 = 6\%$  during the experiments at a full boiler load varied within the range of 2715–3344 mg/Nm<sup>3</sup>, exceeding emissions of SO<sub>2</sub> for the existing PF technology and indicating an even weaker process of binding sulphur oxides in the furnace.

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Received May 18, 2011