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REDUCTION OF NITROUS OXIDE EMISSIONS OF THE BOILER E-135-3,2-420 DG DURING COMBUSTION OF THE GASEOUS OIL SHALE PROCESSING PRODUCTS

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The technological and constructive measures implemented on the boiler E-135-3,2-420 DG are provided, which allow reducing the formation of nitrous oxides during combustion of the gaseous oil shale processing products. By reducing the volumetric heat release rate of the furnace, employing special burners, arranging for a staged combustion and recirculating flue gases, it became possible to ensure stable fuel burning throughout the entire operating range of the boiler with a nitrous oxide concentration in flue gases of less than 100 mg/m^3 (at O_2 = 3%). Incomplete combustion was practically eliminated.

Keywords: boiler; combustion; gaseous oil shale processing products; nitrous oxides; flue gas recirculation; staged combustion.

E-135-3,2-420 DG type boiler was manufactured at the Belenergomash-BZEM, LLC for the electric power plant erected by VKG ENERGIA OÜ, which is a part of the oil shale processing concern VKG AS in Kohtla-Järve (Estonia). This is a drum-type, two-pass, close-coupled, gas-tight boiler with the rated steam generating capacity of 135 tons/h and steam parameters of 3.2 MPa and 420°C. The longitudinal cross-section of the E-135-3,2-420DG boiler is shown in Fig. 1.

The fuel includes the oil shale processing gases, such as semi-coke gas and producer gas, the composition of which is shown in Table 1.

Semi-coke gas as a byproduct (the main product is shale oil) is produced during pyrolysis of fine-grained shale in the rotating retort. A soot resulting from burning solid residues of this process is used as a heat transfer medium.

The oil shale processing, also known as the Galoter process, has been developed by the experts at the Krzhizhanovsky Power Engineering Institute (ENIN) and the Institute of Chemistry (Estonian Academy of Sciences) in the second half of the 20th century. Currently, eight installations of this type are in operation in Estonia. The lower heating value of semi-coke gas, including the gaseous and partially condensed phases of high molecular weight hydrocarbon components, constitutes 44,000 – 50,280 kJ/m^3 or 10,500 – 12,000 kcal/m^3 (under normal conditions).

Producer gas is formed during pyrolysis of lumpy shale in the process known as Kiviter process. During this process, the vertical shafts of gas generators loaded with lumpy shale are exposed to a cross-flow of a gaseous heat transfer medium formed as a result of partial combustion in air of the same producer gas. Gas generators of this type operate in Estonia as well as worldwide since the beginning of the 20th century. The heating value of producer gas under normal conditions constitutes 2720 – 3350 kJ/m^3 (650 – 800 kcal/m^3).

More details about the properties of the oil shale processing gases used as gaseous fuel are provided in [1].

The main fuel for the boiler is semi-coke gas. A semi-coke gas-fired boiler should be able to support the load within the entire range of operating modes. Producer gas is a supplemental fuel intended to be burned together with semi-coke gas at a ratio of 20/80 (based on heat) also within the entire range of loads of the boiler. Despite the substantial difference in the properties of combustible gases, their joint combustion in one burner unit was planned and implemented. Dual-fuel burners (6 burners with the combined thermal capacity of 20 MW) have been designed and manufactured by ENTEH Engineering AS with the participation

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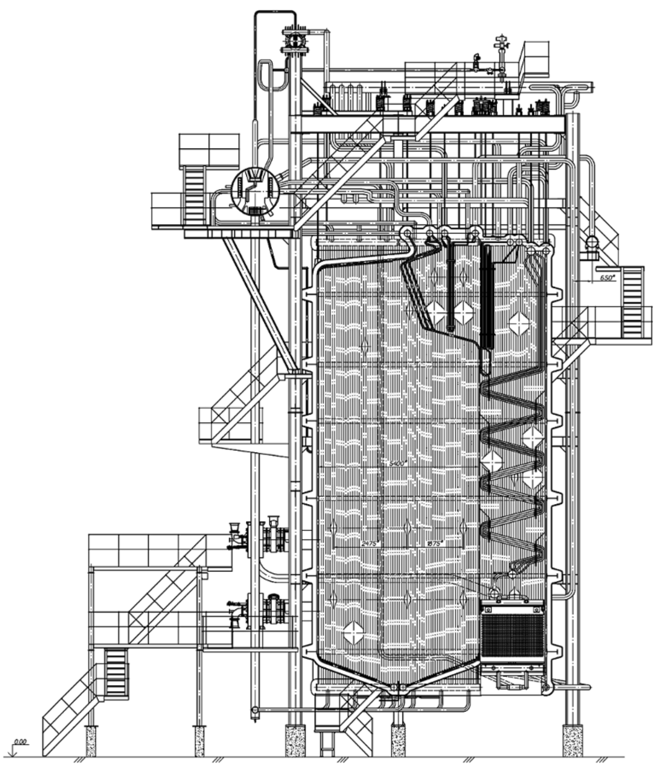

Fig. 1. Longitudinal cross-section of the E-135-3,2-420DG boiler.

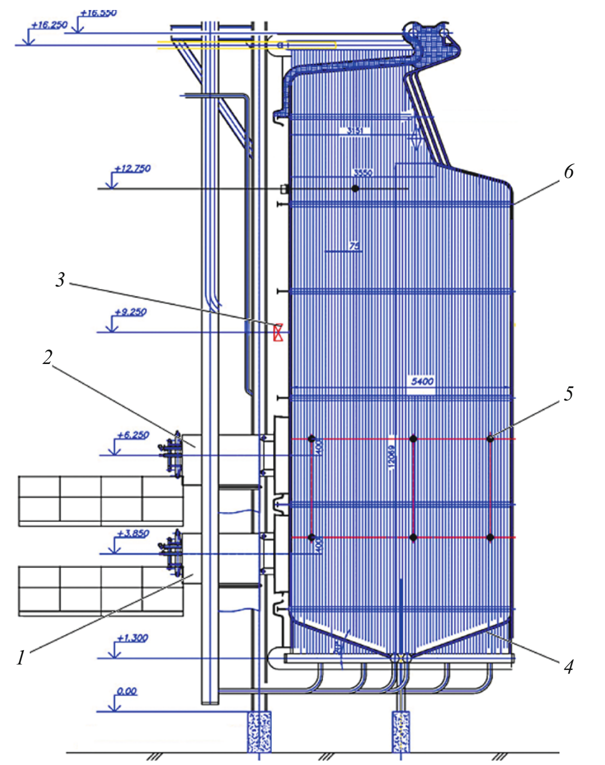

Fig. 2. Schematic of the furnace chamber of the E-135-3,2-420 DG boiler: *1*, lower-tier burners (3 pc.); *2*, top-tier burners (3 pc.); *3*, tertiary air nozzles (3 pc.); *4*, furnace bottom; *5*, peephole mounting points; *6*, buckstays.

of JSC "VTI" based on the existing joint experience in combustion of the specified gases [2].

The key objective during development of the boiler considered in this paper (which is the case with any new gas-fired boiler on the European market) is to ensure allowable atmospheric emissions of the harmful substances. According to the EU Directive 2010/75/EU, the concentration of both NO_x and CO in flue gases should not exceed 100 mg/m^3 (under normal conditions) in terms of the equivalent volume of dry flue gases at O_2 = 3% (for comparison, Russian concentration standards constitute NO_x = 125 mg/m^3 in terms of the equivalent volume of dry flue gases at O_2 = 6%).

The norms of NO_x emissions are quite strict. If trying to achieve such norms only through primary (in-furnace) measures, it becomes necessary to consider the fact that semi-coke gas is a more complex fuel than, for example, natural gas. Its heating value, temperature of adiabatic burning and normal flame propagation velocity are higher. Early experiments on burning semi-coke gas in other boilers have shown that without implementing combined measures (special burners, staged burning, recirculation of flue gases) the standard level of NO_x emissions cannot be achieved. For example, in boilers BKZ-75-39 FSl re-engineered for semi-coke gas combustion, the concentrations of NO_x constituted up to 500 – 650 mg/m^3 [1]. By combining any two of the three above-mentioned measures in these same boilers al-

TABLE 1. Composition of Char and Producer Gases Formed During Thermal Processing of Estonian Oil Shales

Component	Content (volumetric fraction), %	
	Producer gas	Semi-coke gas
Hydrogen (H_2)	4.70 – 6.80	8.85 – 17.52
Carbon monoxide (CO)	3.40 – 6.30	8.17 – 12.97
Methane (CH_4)	1.30 – 2.00	10.55 – 21.40
Saturated hydrocarbons ($Ñ_2Í_6$, $Ñ_3Í_8$, $Ñ_4Í_{10}$)	0.34 – 0.83	7.79 – 13.68
Unsaturated hydrocarbons ($Ñ_2Í$4, $Ñ_3Í_6$, $Ñ_4Í_8$)	0.57 – 1.25	12.96 – 23.84
High molecular weight hydrocarbons (C_5 and above)	0.10 – 0.91	3.73 – 11.19
Nitrogen (N_2)	64.40 – 70.20	2.42 – 26.84
Carbon dioxide (CO_2)	13.40 – 19.20	2.68 – 13.57
Hydrogen sulfide (H_2S)	0.23 – 0.54	0.87 – 3.30

a b

Fig. 3. Boiler unit No. 4 installed at the VKG ENERGIA OÜ electric power station in Kohtla-Järve (Estonia): *a*, general view; *b*, burners for shale processing gas combustion.

lowed to achieve a decrease in the level of emissions to 150 – 200 mg/m^3 or lower. Therefore, in this project it was decided to actively employ all three specified measures.

A constructive way to reduce the formation of NO_x is to decrease the maximum and average fuel combustion temperature by arranging for an intensive cooling of the active burning zone. This can be achieved by increasing the area of the protecting screening surfaces, which receive thermal radiation, as well as increasing the efficiency of such reception. The choice of the number of burners and their tiers is also very important. Multitier configuration of the burner units allows increasing the size of the active burning zone, while reducing the heat release rate at the same time.

To ensure achieving standard parameters in terms of NO_x concentrations in flue gases of the E-135-3,2-420 DG boiler, JSC "VTI" together with ENTEH Engineering AS have developed recommendations and technical solutions with respect to design of the furnace depicted in Fig. 2.

To reduce the volumetric heat release rate, the furnace dimensions were slightly increased in comparison with the conventional natural gas-fired boilers. Also it was decided not to cover the furnace bottom with thermal insulation material. A double-tier burner arrangement in the furnace was chosen with three burners per row on the front wall and the distance between tiers equal to 2400 mm. Such arrangement of the burners along with their relatively low capacity (due to increased number of burners) has also allowed to reduce the heat release rate from the burning zone. Three tertiary air nozzles were located at the distance of 3000 mm above the top-tier burners to allow for the staged combustion. It should be noted that the burner arrangement and dimensions of the furnace do not contradict the recommendations provided in OST 108.836.05–82 [3].

The gas burners installed in the E-135-3,2-420 DG boiler consist of two sections. The capacity of the central part of the burner, intended for burning gas in a strongly swirled stream of clean air, is relatively low (5 – 10% of the overall thermal

TABLE 2. Maximum Achievable Concentrations of NO_x and CO in the Oil Shale Processing Gas Combustion Products Obtained in the E-135-3,2-420 DG boiler (unit No. 4, EPP VKG ENERGIA OÜ, Kohtla-Järve (Estonia)

Parameter	Concentration, mg/m^3 (in terms of 3% O_2 under normal conditions)			
	NO_{δ}	CO	NO_{δ}	CO
Load	100% (135 tons/h)		70% (95 tons/h)	
Semi-coke gas operation	48	0 – 4	37	0 – 3
Semi-coke gas/producer gas mixture operation (80% to 20% ratio based on heat)	39	0 – 3	36	0

capacity of the burner). This is a pilot type burner. The main portion of gas (90 – 95%) is supplied to the peripheral portion of the burner, where it is burned in a stream of a mixture of air and recirculation flue gases. The presence of a stable torch in the central portion of the burner allows to considerably increase the recirculation fraction of flue gases into the peripheral portion without a danger of flame blow-off in the entire burner in general. The recirculating flue gases are captured directly downstream of the boiler at an average temperature of 210 – 220°C. Producer gas is also supplied to the peripheral portion of the burner. The inert components contained therein play the same role as recirculation flue gases.

The considered measures were aimed at influencing the formation of thermal and "fast" nitrous oxides, since both shale processing gases (based on the chemical analysis data) practically lack nitrogen-containing components, which could have determined the appearance of "fuel" nitrous oxides.

Based on the recommended dimensions of the furnace chamber, Belenergomash-BZEM, LLC has completed the configuration and thermal calculation of the boiler, including the calculation of the heating surface characteristics necessary for ensuring the required steam parameters, as well as reliable and economic operation of the boiler in general.

The E-135-3,2-420 DG boiler was assembled in 2017, and commissioned in December at the electric power plant operated by VKG ENERGIA OÜ (Fig. 3).

The measurements of the boiler emissions performed in the process of acceptance tests have shown the legitimacy of the chosen decisions: the concentration of nitrogen oxides in flue gases within the entire operating range of the loads of the E-135-3,2-420 DG boiler was less than the allowable limit of 100 mg/m^3 (under normal conditions). An incomplete combustion was practically eliminated. The measurements were performed by the authors of this paper using a gas analyzer with electrochemical cells Testo 330-2 LX, as well as by the staff of the Tallinn University of Technology who used a multicomponent gas analyzer GASMET DX-4000 capable of conducting measurements in the infrared spectrum.

In the process of further tests conducted purely for research purposes to evaluate the limits of the burner abilities with respect to this boiler, as well as the combustion technology, the modes of operation were identified, during which the NO_x concentration in flue gases was more than twice lower compared to the values regulated by the European norms (Table 2).

The obtained positive experience in this project, associated with the reduction of NO_x formation, can be used when designing other boilers burning similar non-standard gaseous fuels, such as coke gas and blast-furnace gas in metallurgy, and pyrolysis gases in petrochemistry.

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