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CALCULATION ANALYSIS OF SHALE OIL AND POWER COGENERATION

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Abstract. *Shale oil and power cogeneration (SPC) technology, which uses the high-temperature ash of a circulating fluidized bed (CFB) boiler as a solid heat carrier (SHC) for retorting oil shale in the retorting equipment, was analyzed by a mathematical model. The parameters and relationships of SPC technology dependent on the initial temperature of SHC and the heating value of oil shale were calculated. The application of SPC technology with a condensing turbine allows approximately 2.5 kWh electricity to be generated per one kilogram of shale oil. In the retorting process, the calculated relationship SHC/oil shale as received is in the range of 1.7–1.9 if the temperature of SHC is 750 °C. The application of SPC technology increases the content of* CO_2 *and water vapour in the flue gas in the CFB boiler.*

Keywords: *shale oil and power cogeneration, calculation analysis, mathematical model, circulating fluidized bed, solid heat carrier.*

1. Introduction

The basic idea of shale oil and power cogeneration (SPC) is the application of the ash circulating in a circulating fluidized bed (CFB) [1] boiler as a high-temperature solid heat carrier (SHC), combining CFB combustion technology with rotating retort drum processing [2]. A detailed description of the features of shale oil and power cogeneration and its benefits is presented by Ots et al. [3, 4].

Figure 1 shows the SPC technological scheme. The oil shale is dried with the hot flue gas in the dryer outside the drum reactor and is separated from the drying agents in the cyclone separator. The drying agents, with oil shale dust (approximately 1% of dry oil shale), are fed back into the furnace of the CFB boiler. The ash from the CFB furnace and the dry oil shale are directed into the mixing chamber where they are mixed and transferred to the retort drum.

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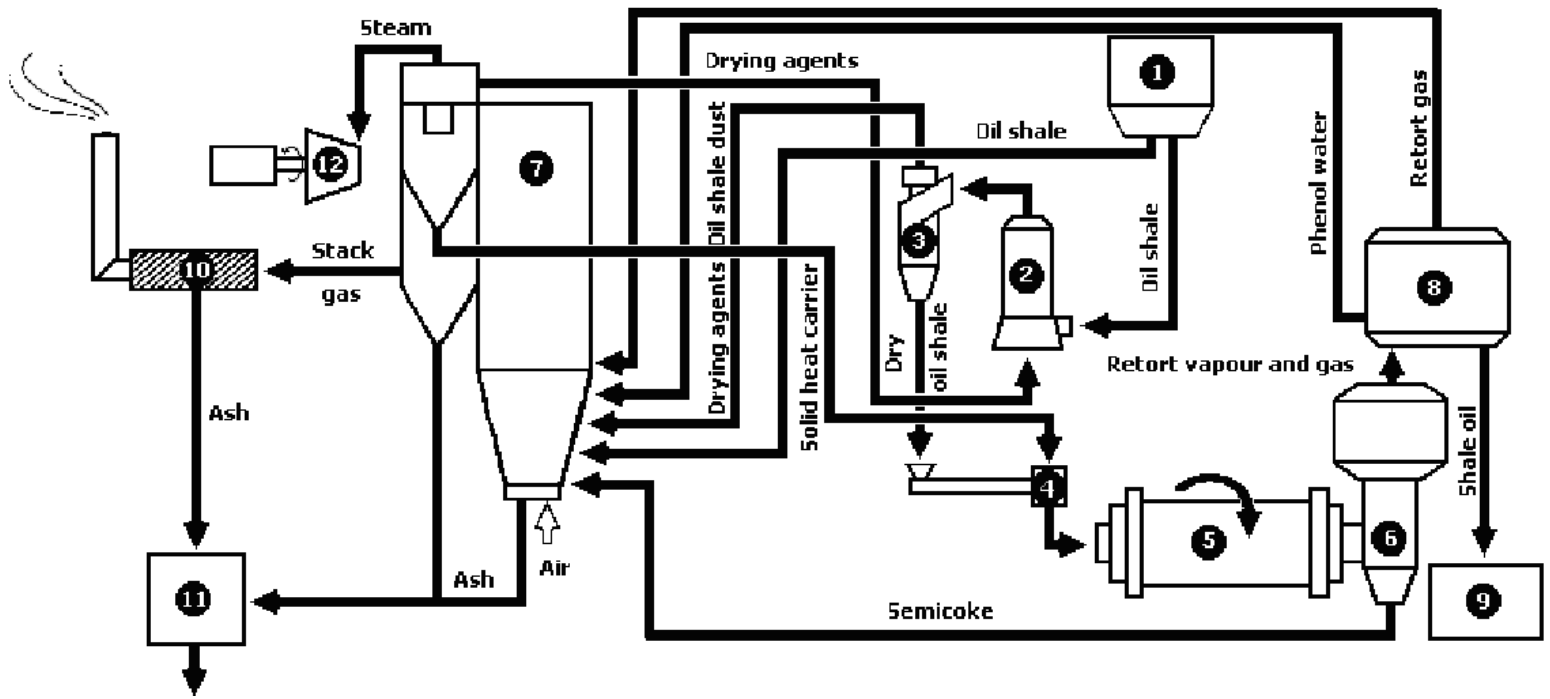

Fig. 1. SPC technology schema. 1 – oil shale storage, 2 – dryer, 3 – cyclone of dry oil shale, 4 – mixer of SHC and oil shale, 5 – rotating retort reactor, 6 – separator of oil vapour and semi-coke, 7 – CFB boiler, 8 – condenser of oil vapour, 9 – shale oil storage, 10 – flue gas cleaner, 11 – bottom and fly ash bunker, 12 – turbo-generator for power production.

After the retort drum, the gaseous retort products are separated from the semi-coke in the separator. The semi-coke is then fed into the CFB boiler furnace. Semi-coke here is understood as a mixture of semi-coke and SHC (ash). The shale oil is separated from the gaseous retort products in the condenser and directed into the storage collection. The retort gas and pyrogenous water are fed into the furnace of the CFB boiler. In the boiler, heat for steam generation is received from the combustion of the retorting process co-products: semi-coke and high-caloric retort gas, but also from the sensible heat of semi-coke and the direct firing of oil shale.

A mathematical model of SPC technology was elaborated for the calculative analysis of the technological process.

The analysis of SPC technology is based mostly on the equipment operating currently at Eesti Energia, the Foster Wheeler CFB boiler, with an electrical capacity of 107.5 MW, and the Enefit retort drum, with an oil shale input capacity of 280 tons of oil shale per hour.

2. Calculation data

The model for the analysis of SPC technology consists of:

1. thermal and mass balances of the oil shale dryer before retorting
2. thermal and mass balances of the retort drum
3. thermal and mass balances of the CFB boiler integrated with the retort drum

The main parameters affecting the SPC process are the heating value of oil shale and temperatures of ash for retorting and semi-coke entering the CFB furnace.

The heating value of oil shale is an integral indicator of oil shale quality. Despite the fluctuation of the composition of oil shale, there is a firm relationship between the technical characteristics and heating value of oil shale. The heating value of dry matter in oil shale depends on the content of ash and carbonate carbon dioxide in the fuel. The heating value of as-received matter depends additionally on the moisture in the fuel. It enables, on the basis of statistical data, a correlation to be established between the heating value of oil shale and the contents of ash, carbonate carbon dioxide and moisture in the fuel [5–8]. The subsequent calculations are based on Estonian oil shale data [5].

The heating value of oil shale as received was chosen in the range of 7–12 MJ/kg. The energy distribution of oil shale organic matter in the decomposition process was as follows:

53.5% shale oil
18.0% retort gas
23.5% semi-coke
5 % pyrogenous water

Table 1 presents the other main initial data selected for the calculations.

Table 1. The main initial data selected for the calculations

Initial temperature of oil shale entering the dryer, °C	20
Temperature of drying gas from the boiler, °C	500
Temperature of drying gas after the dryer, °C	150
Temperature of oil shale after drying, °C	120
Temperature of ash (SHC) for retorting, °C	750*
Temperature of semi-coke entering the furnace, °C	500
Temperature of retort gas and pyrogenous water entering the furnace, °C	20
Extent of decomposition of carbonates in the CFB furnace	0.7
Excess air factor	1.2

* For comparison, in some calculations, the temperature of SHC was set at 800 °C.

3. Main heat fluxes in the shale oil and power cogeneration

Figure 2 shows the main heat fluxes in the shale oil and power cogeneration related to the heat balance of the boiler.

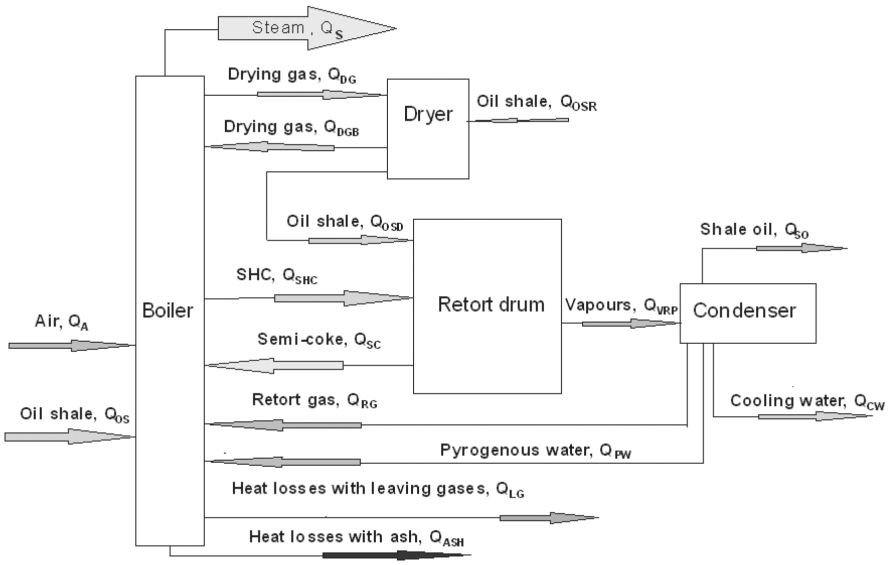

Fig. 2. Heat fluxes in the SPC schema. Denotations: Q_{SHC} – quantity of heat released from the boiler with a solid heat carrier; Q_{DG} – quantity of heat released from the boiler with flue gas for drying oil shale before retorting; Q_{DGB} – quantity of heat with gas returning from the dryer; Q_{OSR} – sensible heat of oil shale before drying; Q_{OSD} – sensible heat of oil shale after the dryer; Q_{SC} – quantity of heat with semi-coke from the retort drum into the boiler; Q_{VRP} – sensible heat of volatile products of retorting; Q_{RG} – quantity of heat with retort gas into the boiler; Q_{PW} – quantity of heat into the boiler with pyrogenous water; Q_{SO} – sensible heat of shale oil after condensation; Q_{CW} – quantity of heat transferred to the cooling water in the condenser; Q_{OS} – quantity of heat into the boiler with oil shale from the bunker; Q_A – sensible heat of combustion air; Q_S – quantity of heat leaving the boiler with steam; Q_{LG} – heat losses with leaving flue gas; Q_{ASH} – heat losses with ash.

The heat losses due to the external cooling of the boiler and the retort drum are not shown in the schema.

In the SPC unit firing only oil shale retorting co-products, the computational heat fluxes for the preliminary drying of oil shale and back from the dryer into the boiler are almost equal (Fig. 3). Most of the heat entering the dryer is consumed for drying oil shale and returns to the boiler at a much lower temperature than before the dryer, saved into the water vapour, leaving the boiler with flue gas. The heat of the combustion of oil shale dust carried into the boiler by drying gas compensates approximately for the quantity of heat needed for raising the oil shale temperature in the dryer. Semi-coke is transported into the boiler at a temperature of 500 °C and its sensible heat could be used for steam production. The total quantity of heat entering the CFB boiler furnace with semi-coke is due to the high amount of its sensible heat (about 40% of the total heat entering with semi-coke) approximately

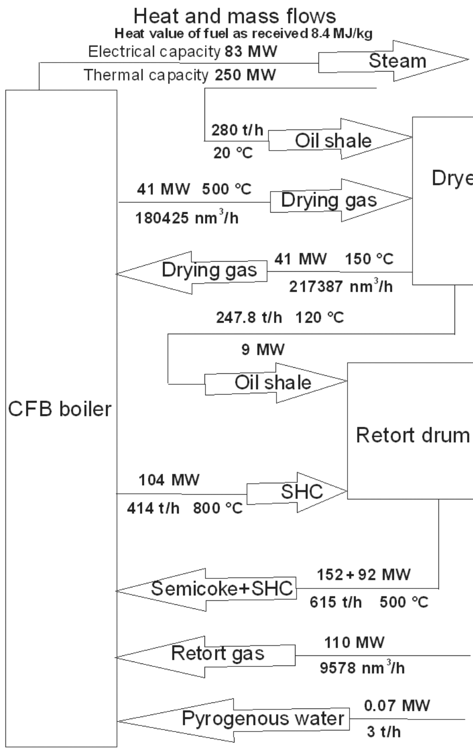

Fig. 3. The heat and mass fluxes in the SPC unit consisting of the CFB boiler and the retort drum with an oil shale input capacity of 280 t/h firing only co-products of oil shale retorting. The extent of carbonate decomposition is 0.7. The heat loss with bottom ash is 9.3 MW and the quantity of heat leaving the condenser with cooling water is 18.3 MW. The quantity of heat entering the furnace of the CFB boiler with semi-coke consists of its heat of combustion (152 MW) and sensible heat.

twice the quantity of heat entering the furnace with retort gas. The highest amount of heat leaving the boiler is that exiting with steam for electricity generation. The quantity of heat for retorting is substantially smaller (Fig. 3).

4. Some calculated parameters characterizing the SPC process

The quantity of solid heat carrier needed for retorting one mass unit of oil shale depends on the initial temperature of the solid heat carrier and the content of organic matter in oil shale. Increasing the initial temperature of SHC from 750 to 800 °C decreases the quantity of SHC needed for retorting one mass unit of oil shale about 16.5%, with the heating value of semi-coke after retorting increasing about 12% and the generated electricity (kWh) per 1 kg of shale increasing about 2.4%.

Table 2 presents some calculated parameters characterizing the SPC process for the initial temperature of SHC at 750 °C dependent on the heating value of oil shale as received. It follows from the table that the quantity of electricity generated per one kg of shale oil depends only slightly on the heating value of oil shale, about 4% for the range of values of 7–12 MJ/kg. The calculated heating value of semi-coke depends much more on the heating value of oil shale as received, about 48% for the same range of oil shale heating values.

Table 2. The relationship between SHC and oil shale for retorting and generated electricity (kWh)/1 kg shale oil dependent on the heating value of oil shale as received. The temperature of SHC entering the retort drum is 750 °C

Lower heating value of oil shale, MJ/kg	7	8.4	10	11	12
Moisture, %	9.9	10.6	11.4	11.4	12.3
Content of organic matter, %	18.96	23	27.32	30.1	32.9
Content of ash, %	49.84	47.4	44.28	42.9	40.3
Content of carbonate CO_2, %	20.3	18	16	14.6	13.5
Heating value of semi-coke, MJ/kg	0.67	0.79	0.93	1.01	1.09
SHC/oil shale as received	1.67	1.75	1.83	1.89	1.94
SHC/dry oil shale	1.85	1.96	2.07	2.13	2.21
kWh/1 kg produced shale oil	2.43	2.46	2.50	2.51	2.52

5. The quantity of electrical power obtained from firing the co-products of shale oil

An SPC technology unit firing exclusively co-products of shale oil production was considered to assess the possible quantity of electrical output from the combustion of semi-coke and retort gas, with no additional oil shale from the bunker used. Four retort drum capacities – 70, 140, 280 and 560 t/h –

were considered. Figure 4 shows the results. It follows from the figure that the Foster Wheeler CFB boiler with a nominal electrical capacity of 107.5 MW fits quite well with the Enefit retort drum with an oil shale input capacity of 280 t/h if the heating value of oil shale is about 11 MJ/kg. The quantity of electrical power produced by firing semi-coke and retort gas in a CFB boiler depends on the heating value of oil shale as received linearly (Fig. 5).

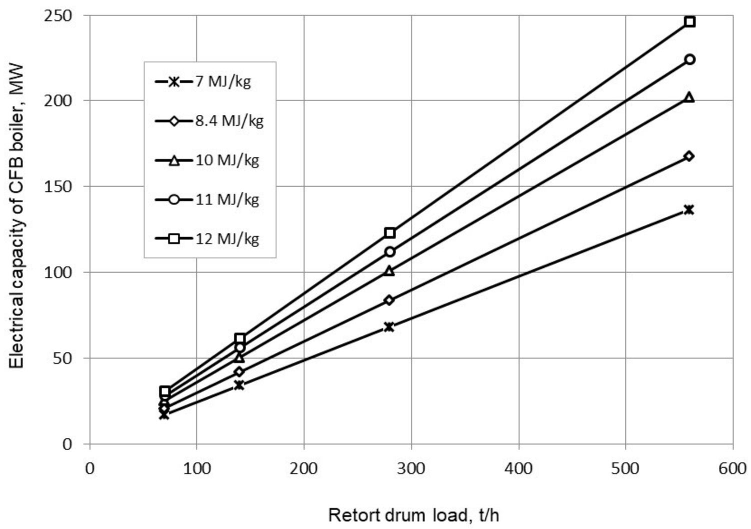

Fig. 4. The electrical capacity of the CFB boiler dependent on the load of the integrated retort drum and the heating value of oil shale as received, if exclusively the co-products of the oil shale retorting process were fired.

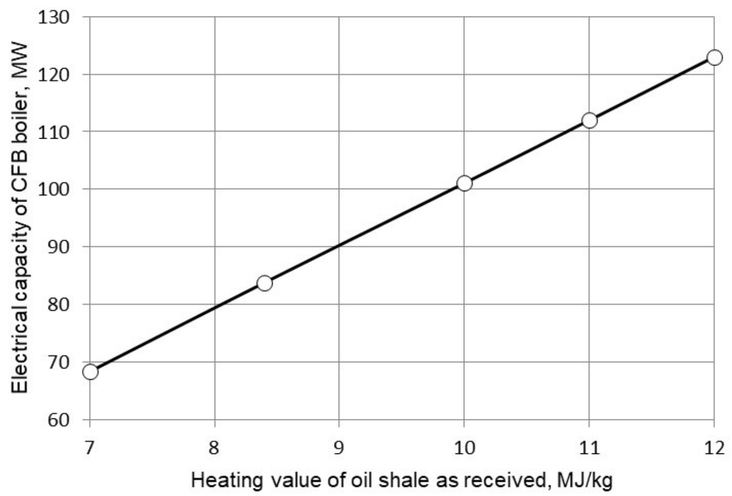

Fig. 5. The electrical capacity of the CFB boiler dependent on the heating value of oil shale as received for the integrated retort drum load of 280 t/h.

6. The impact of shale oil and power cogeneration on the composition of flue gas leaving the boiler

If the oil shale-fired CFB boiler integrates with the retort drum, then the composition of flue gas at the boiler outlet changes. The content of CO_2 and water vapour in the flue gas increases dependent on the contribution of semi-coke and retort gas to electricity generation if oil shale from the bunker is used as additional fuel (Fig. 6). The nonlinearity of said dependence at a low contribution of semi-coke and retort gas to electricity generation is caused by the change of the extent of decomposition of carbonates in semi-coke entering the CFB boiler furnace. If the quantity of ash circulating as SHC is small, then the extent of the decomposition of carbonates for most of the ash is equal to the extent of the decomposition of carbonates in a common CFB furnace. With an increased SHC percentage in the entire ash, more ash circulates through the retort drum and the furnace, passing through the furnace more times. As a result, the extent of the decomposition of carbonates increases. The content of CO_2 and water vapour in the flue gas also depends on the composition of oil shale (the ratio between organic matter, ash, moisture and carbonaceous CO_2), which could be characterised by the heating value of oil shale (Fig. 7).

The emissivity of flue gas increases due to the increased content of CO_2 and water vapour. This should be considered in the designing of boiler heat exchange surfaces.

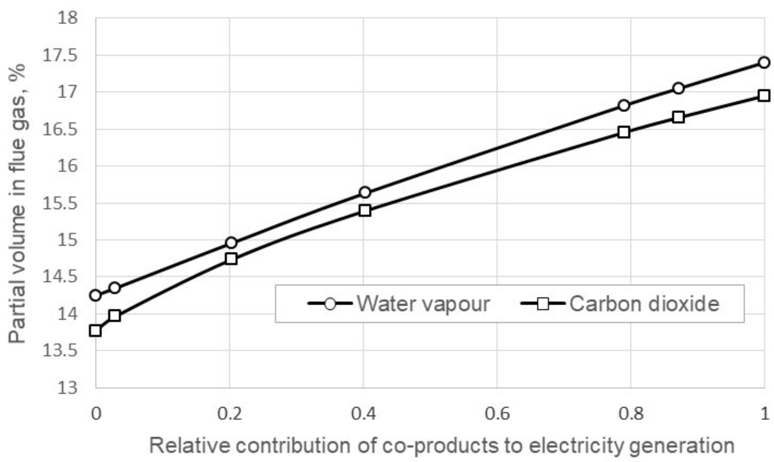

Fig. 6. The content of CO_2 and water vapour in the flue gas dependent on the contribution of semi-coke and retort gas to electricity generation. The heating value of oil shale as received is 8.4 MJ/kg.

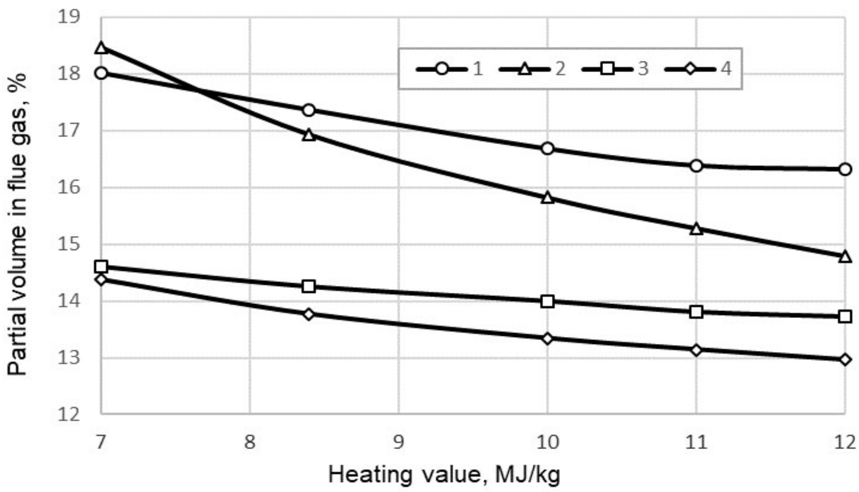

Fig. 7. The content of CO_2 and water vapour in the flue gas dependent on the heating value of oil shale as received. 1 – water vapour at combustion of semi-coke and retort gas; 2 – CO_2 at combustion of semi-coke and retort gas; 3 – water vapour at oil shale combustion; 4 – CO_2 at combustion of oil shale.

7. Production of CO_2 per one kWh of generated electricity

The heat released in a CFB boiler integrated with a rotary drum reactor is divided into two parts:

1. heat for electricity generation, including heat losses related to the generation;
2. heat for oil shale retorting, including heat loss due to the external cooling of the retort drum.

The quantity of CO_2 at the boiler outlet is proportionately distributed between these heat quantities. The analysis shows that the application of SPC technology increases the content of CO_2 in the flue gas and the quantity of CO_2 per one kWh of produced electricity as well, compared with the condensing boiler fired only with oil shale. Figure 8 illustrates the relative increase in the quantity of CO_2 per one kWh of produced electricity in the application of SPC technology dependent on the contribution of semi-coke and retort gas to electricity generation. The absolute value of CO_2 per one kWh of produced electricity is in the range of 0.92–1.35 kg, dependent on the contribution of co-products to electricity generation.

Production of one kg shale oil generates 0.21–0.29 kg CO_2 dependent on the contribution of semi-coke and retort gas to the production. It is approximately 7–10% of the quantity of CO_2 forming in the combustion of shale oil.

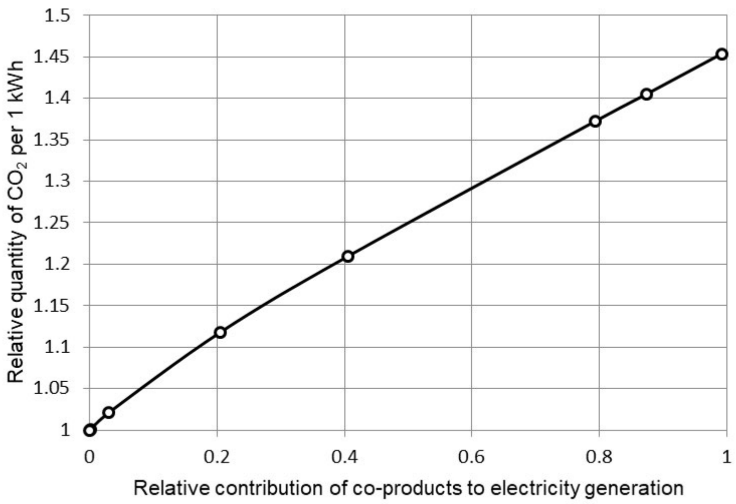

Fig. 8. The relationship between the quantity of CO_2 per one kWh of produced electricity in the application of SPC technology to the quantity of CO_2 per one kWh of produced electricity in burning only oil shale dependent on the contribution of co-products to electricity production.

8. The distribution of ash leaving the CFB furnace in the SPC technology unit

The ash leaving the CFB furnace divides into two parts. One part leaves the CFB furnace as bottom ash. The cyclone after the furnace separates the other part into fly ash carried away with flue gas and the ash for the INTREX-superheater and solid heat carrier for oil shale retorting. SHC and ash for superheating return to the furnace, forming two contours of circulating ash. The capacity of the boiler determines the quantity of ash circulating in the superheater contour. The ash flow through the Foster Wheeler CFB INTREX superheater must insure the required steam temperature at the boiler outlet. The measurements show that for the Foster Wheeler CFB boiler with an electrical capacity of 107.5 MW at Narva Power Plants, the ash flow needed for keeping the nominal steam outlet temperature is approximately 283 kg/s, if the ash temperature in the INTREX superheater is in the range of 760–620 °C. The quantity of ash needed as a solid heat carrier for retorting depends proportionately on the drum capacity, the initial temperature of SHC and the heating value of oil shale. For the Enefit 280 t/h retort drum, the calculated SHC rate is approximately 136 kg/s if the initial temperature of SHC is 750 °C and the heating value of oil shale as received is 8.4 MJ/kg. Therefore, the largest mass circulates in the contour of the INTREX superheater. The amount of ash used as a solid heat carrier for retorting is substantially lower, but it noticeably increases the ash circulation rate in the FCB furnace. Figure 9 illustrates the relative distribution of ash leaving the

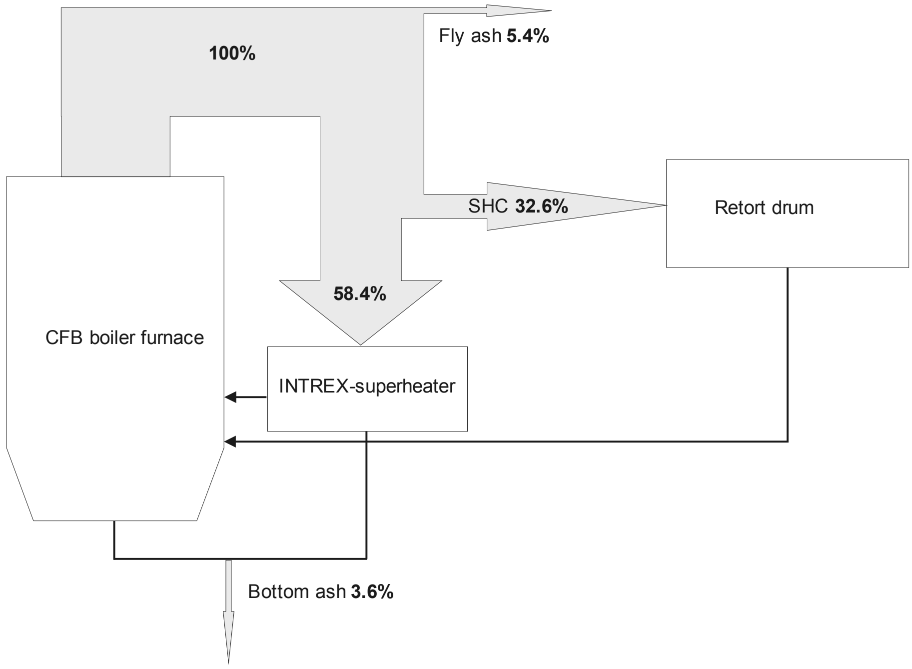

Fig. 9. The approximate relative distribution of ash flow leaving the furnace of the CFB boiler with an electrical capacity of 107.5 MW, integrated with the retort drum with an oil shale input capacity of 280 t/h. The heating value of oil shale as received is 8.4 MJ/kg and the initial temperature of SHC is 750 °C. The temperature in the INTREX superheater is in the range of 760–620 °C.

furnace of the CFB boiler with an electrical capacity of 107.5 MW integrated with the retort drum with a capacity of 280 t/h. The relation of bottom ash (Fig. 9) to the total amount of ash leaving the boiler is 40%. The measured relation is in the range of 30–37%, dependent on the heating value of oil shale as received [9].

9. Conclusions

The parameters and relationships of the shale oil and power cogeneration technology were calculated on the basis of thermal and mass balances of the retort drum, the circulating fluidized bed boiler integrated with the retort drum and the oil shale dryer.

The parameters of SPC technology depend on the initial temperature of solid heart carrier and the heating value of oil shale. Increasing the initial temperature of SHC from 750 to 800 °C decreases its quantity needed for retorting one mass unit of oil shale about 16.5%, the heating value of semi-coke increases about 12% and the amount of generated electricity (kWh) per one kg of shale oil increases about 2.4%.

At an initial temperature of SHC of 750 °C, the calculated parameters of SPC technology dependent on the heating value of oil shale as received were as follows:

- The electrical power generated per one kilogram of produced shale oil was 2.4–2.5 kWh.
- The calculated heating value of semi-coke (actually semi-coke + ash) was in the range of 0.7–1.1 MJ/kg.
- In the retorting process, the calculated relationship between the solid heat carrier and oil shale as received was in the range of 1.67–1.94.

The observed heating value of oil shale as received was in the range of 7–12 MJ/kg.

The application of SPC technology increased the content of CO_2 and water vapour in flue gas after the CFB boiler furnace and the formation of CO_2 per one kWh of generated electricity and per one kilogram of produced shale oil as well. As a result, the emissivity of flue gas increased.

The INTREX-superheater used most of the ash leaving the furnace of the CFB boiler. The amount of ash used as a solid heat carrier for retorting was substantially lower.

The Foster Wheeler CFB boiler with an electrical capacity of 107.5 MW was found to be suitable for utilization of semi-coke and retort gas produced in the Enefit new rotary drum reactor with an oil shale input capacity of 280 t/h.

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