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TECHNICAL AND ECOLOGICAL ASPECTS OF SHALE OIL AND POWER COGENERATION

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The most substantial feature of shale oil and power cogeneration is the technology that uses the high-temperature solid phase from the ash separator of a circulating fluidised-bed (CFB) boiler as the heat carrier in the rotating drum reactor in oil shale retorting equipment rather than high-temperature ash from a single-purpose built-in semi-coke burning furnace. Retort products generated in the rotating drum reactor are separated from semi-coke in the separator and canalised into the condensing and cleaning equipment. Semi-coke is transported into the CFB furnace. All co-products generated in this technological process, such as phenol water, drying agent containing oil shale particles etc., are defused in the furnace of the CFB boiler. The application of such technology makes it possible to minimise the dangerous waste of shale oil production and guarantee the maximum use of oil shale energy.

Introduction

The rise of oil prices in the global market has increased the interest in production of oil from oil shale in Estonia and other countries as well. The greatest problem of shale oil production is low thermal efficiency of the process.

Figure 1 shows the theoretical **(retorting in standard Fischer Assay)** energy balance of thermal decomposition of oil shale organic matter, as well as the real-life balance compiled based on the long-term experience of shale oil production with the solid heat carrier (SHC) method at the AS Narva Oil Plant Company.

As seen from Fig. 1, the energy contained in the organic matter of oil shale becomes divided in the retorting process into four main components from which approximately 2/3 accumulates into oil.

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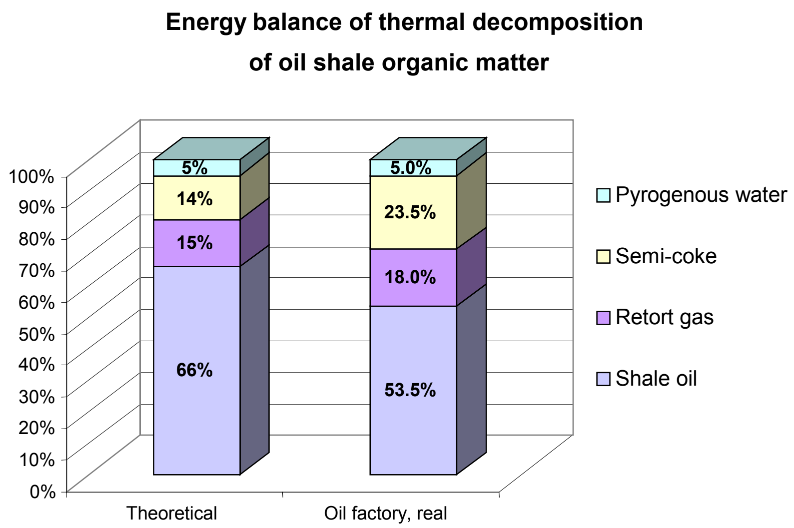

Fig. 1. Energy balance of thermal decomposition of oil shale organic matter. Theoretical means energy balance by retorting in standard Fischer Assay.

Nowadays, in the case of applying SHC technology, the energy of the retort gas is not used. The relation Q_V/Q_T is approximately 0.54 (Q_V – the energy accumulated into shale oil MJ/kg, Q_T – the calorific value of oil shale MJ/kg).

According to the technological scheme applied at AS Narva Oil Plant, the retort gas is transported into furnaces of pulverised oil shale-burning boilers at the nearby Estonian Power Plant and the heat released produces steam for power generation. At the same time 80% of the sulphur compounds contained in the retort gas are bound with fly ash in the boiler. The rest of the sulphur compounds in retort gas are emitted into the atmosphere. The pyrogenous water contaminated with resolved phenols is also transported into the same boiler furnaces for defusing.

The semi-coke is burned in the SHC equipment – the aero-fountain furnace – for producing heat carrier at the approximate temperature of 800 °C.

This paper deals with the possibility of using a large part of heat (0.46) released in shale oil production for power generation.

The basic idea proposed in [1] is the suggested process for application of the ash circulating in a CFB boiler as a solid high-temperature heat carrier, integrating this boiler with a rotating retort drum. In the boiler, the heat for steam generation is received from burning of retorting process products, such as semi-coke and high-calorific retort gas. Burning of additional oil shale is also possible in the CFB boiler. The steam from the CFB boiler is applied for power generation and, if needed, for cogeneration of power and heat or for other technological purposes.

Shale oil and power cogeneration significantly simplifies the process, compared with the individual schemes for shale oil and power production, because the equipment rounding the retorting drum (the furnace for burning semi-coke, distilled gas and phenol water formed in the process, ash separators, recovery boiler, etc.) is combined into one unit – the CFB boiler. Below combined cogeneration of shale oil and power is denoted with abbreviation SPC.

The application of the SPC technology with a condensing turbine allows to produce approximately 2–3 kWh electrical power per one kilogram of shale oil.

SHC process

Currently the best technology for shale oil production (regardless of great energy losses) is the SHC method. The basic idea of this process is leading oil shale and high-temperature heat carrier (ash) into direct contact. As a result, the temperature of the mixture achieves the most appropriate value from the point of view of oil production: 450–500 °C. The high-temperature ash is received from burning semi-coke in the aero-fountain combustor (AFC) of the retort with subsequent separation of the ash from the gas flow in mechanical separators.

The principal scheme of the SHC process is presented in Fig. 2 [2]. This scheme (not in full extent) is applied at AS Narva Oil Plant (retort UTT-3000).

This technology enables treatment of oil shale fines (piece size of up to 25 mm). Oil shale is previously dried in the aero-fountain dryer (AFD) and then thermally decomposed in the rotating drum reactor by the heat transferred from the solid high-temperature heat carrier. The solid waste formed in the drum reactor (semi-coke – containing hydrocarbons not volatilised in the retort and the ash partially impregnated with shale oil) is separated in the sedimentation chamber after the retort drum and transported into the AFC and burned in the reducing environment (excess-air factor $\alpha < 1$) to ensure the required temperature of ash. The temperature in the aero-fountain combustor is 750–850 °C.

The shortage of air causes a substantial content of carbon monoxide and hydrogen sulphide in flue gas forming in the AFC [2]. Flue gas contains also sulphur dioxide and the particles with calcium sulphide soluble in water. Ash leaving with flue gas from the AFC contains a substantial amount of organic carbon as well. The ash-containing flue gas is divided after the AFC into two parts. One part is transported into the separator where the coarse fraction of the ash particles is separated from flue gas and transported into the mixer. Oil shale for retorting is transported from the dryer to the mixer as well. Oil shale mixed with the high-temperature ash is transported into the rotating drum reactor for thermal treatment. The other part of flue gas is transported into the solid fraction separator where ash particles are separated and gas is transported into the AFD.

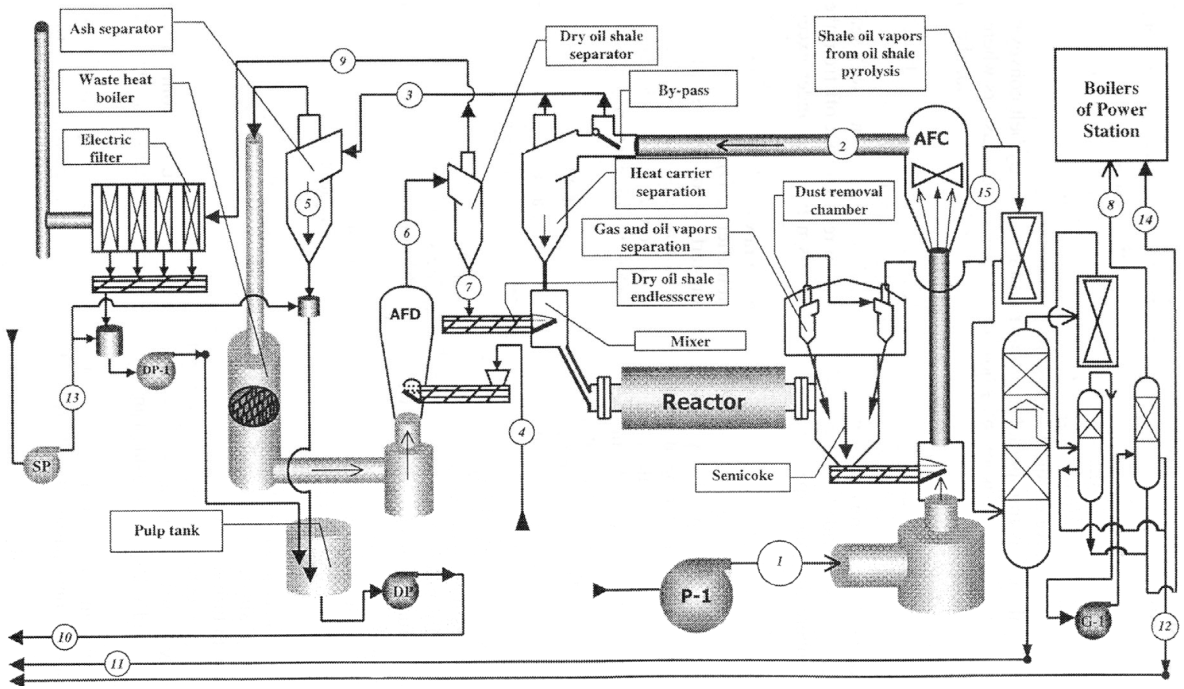

Fig. 2. Principal mass flows diagram of the UTT-3000 retort: (the Galoter process). In more detail in [2].

Reactor – drum reactor for oil shale pyrolysis; Boiler of power station – boilers of the Estonian Power Plant; AFC – aero-fountain combustor; AFD – aero-fountain dryer; P-1 – air blower; DP – dredger pump; DP-1 – small dredger pump of electric precipitators; SP – pump for settled recycle water; G-1 – gas blower.

1 – compressed air into the retort; 2 – SHC mixture with flue gas after combustion of semi-coke in the AFC; 3 – ash and flue gas mixture after separation of SHC required for the oil shale pyrolysis process; 4 – raw oil shale to pyrolysis in the retort; 5 – ash separated by ash cyclones of the 1st, 2nd and 3rd stages; 6 – dried oil shale mixture with flue gas after the AFD; 7 – dried oil shale separated by cyclones of the 1st, 2nd and 3rd stages prior to entering the system of the dry oil shale screw conveyers; 8 – retort gas to firing in the power station boilers; 9 – flue gas to the electric precipitator for final purification; 10 – ash pulp of the retort to No. 4 dredger unit of the power station; 11 – shale oil to fuel storage; 12 – oil shale gasoline separated from water to storage; 13 – settled recycle water to washing facilities of the ash hydro-removal system of the retort; 14 – retort phenol water to incineration in power station boilers; 15 – oil vapours after cleaning to the condensation system.

After leaving the dryer the moist drying agents (gas) are cleaned in the electrostatic precipitator from oil shale particles and then emitted into the atmosphere. The oil shale dust (approximately 1% of the oil shale calorific value) is not used and is emitted with the ash into the ash hydro-removal system. The uncondensed retort gas of high calorific value is burned in the pulverised oil shale boilers. The phenol water formed in the retorting process is also introduced and atomised in the boiler combustor at the same power plant.

A waste heat boiler in the scheme of the UTT-3000 predecessor of the SHC unit served for burning of the gas not completely burned in the aero-fountain combustor and cooling down flue gases to 600 °C. An air preheater (not shown in this figure), using ash heat from the ash separator before the waste heat boiler for heating the air up to 300 °C, was also in the scheme of the UTT-3000. Thermal effectiveness of the waste heat boiler and the air preheater was very low due to the intensive forming of sulphate ash deposits on heating surfaces. Because of their complicated operation they are not used in the SHC scheme.

Water is sprayed into the flue gas to ensure the necessary temperature (600 °C) for drying of oil shale.

CFB technology

The design of the oil shale-burning CFB boiler is presented in Fig. 3. Boilers of this type are operated at AS Narva Power Plants [3].

The combustion process of solid fuel in the CFB boiler is based on the aerodynamic fast regime of the two-phase system (solid particles and gaseous environment). Previously ground fuel particles and air are directed into the furnace so that the total air amount exceeds the stoichiometrically required air amount. The bed material for coal burning is usually sand. If oil shale is burned, there is no need for sand because the bed is formed from ash. The operation has shown that oil shale ash ensures stable operation of boilers. In the case of oil shale there is also no need to feed into the furnace any absorbent for flue gas desulphurisation. The calcium contained in oil shale replaces the sulphur absorbent. After the furnace the flue gas with the ash is directed into the separator, where the coarse fraction of the ash is separated from flue gas and directed from the sedimentation chamber directly or through the heat exchanger back into the furnace. As a result, a permanent circulating circuit of ash particles is formed.

Burning of oil shale in CFB boilers has been effective. The thermal efficiency of the boiler is 90–92%. The combustible matter content of ash does not exceed 0.1–0.2%, and the concentration of carbon monoxide and sulphur dioxide in flue gas is almost zero.

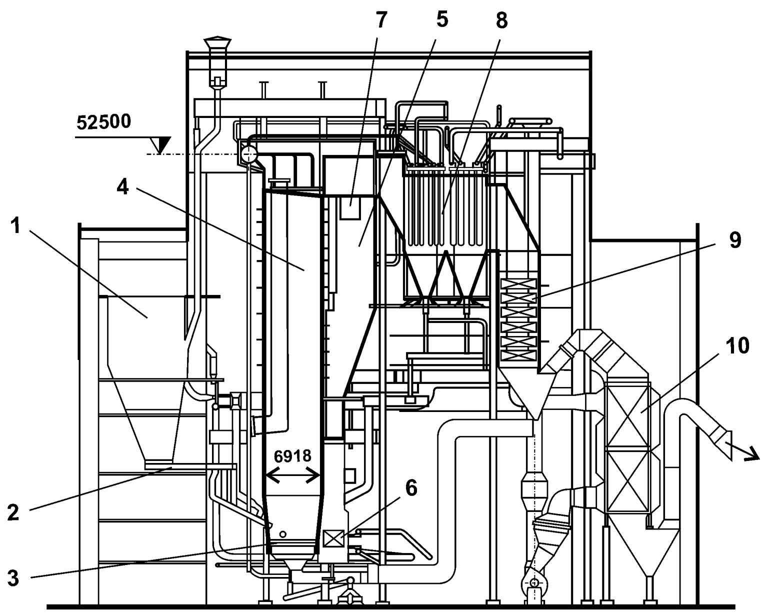

Fig. 3. Oil shale burning in a circulating fluidised-bed boiler.

1 – oil shale bunker, 2 – fuel feeder, 3 – grate, 4 – furnace, 5 – precipitation chamber, 6 – fluidised-bed heat exchanger, 7 – separator, 8 – superheater, 9 – economiser, 10 – air preheater [3].

SPC technology

The advantage of the new technology lies in the combination of the SHC and CFB processes.

As shown above, the SHC technology requires, in addition to the retort drum, various auxiliary equipment: a furnace of a specific design for semi-coke burning, separators for separation of ash from the flue gas, ash heat exchanger and boiler for utilization of ash and flue gas energy. Furthermore, if there is no power plant nearby where the toxic co-products of shale oil production could be safely utilised, a special equipment must be built for neutralisation of these toxic co-products to comply with the current regulations for environment protection.

The benefit of the new SPC technology lies in the replacement of the SHC technology's auxiliary equipment (in the grey frame in Fig. 4) with a CFB boiler. As a result, there is no more need for the semi-coke burning furnace (Fig. 4, pos. 7), distributor (Fig. 4, pos. 13) and ash cyclone separators (Figure 4, pos. 14 and 15). The furnace for utilization of the heat (Fig. 4, pos. 18) and the ash heat exchanger (Fig. 4, pos. 19) are not needed as well. One compact unit, the CFB boiler, replaces all these devices. This simplifies the technological scheme of the oil shale retort process. Above all the improvement of the existing scheme concerns the improvement and opera-

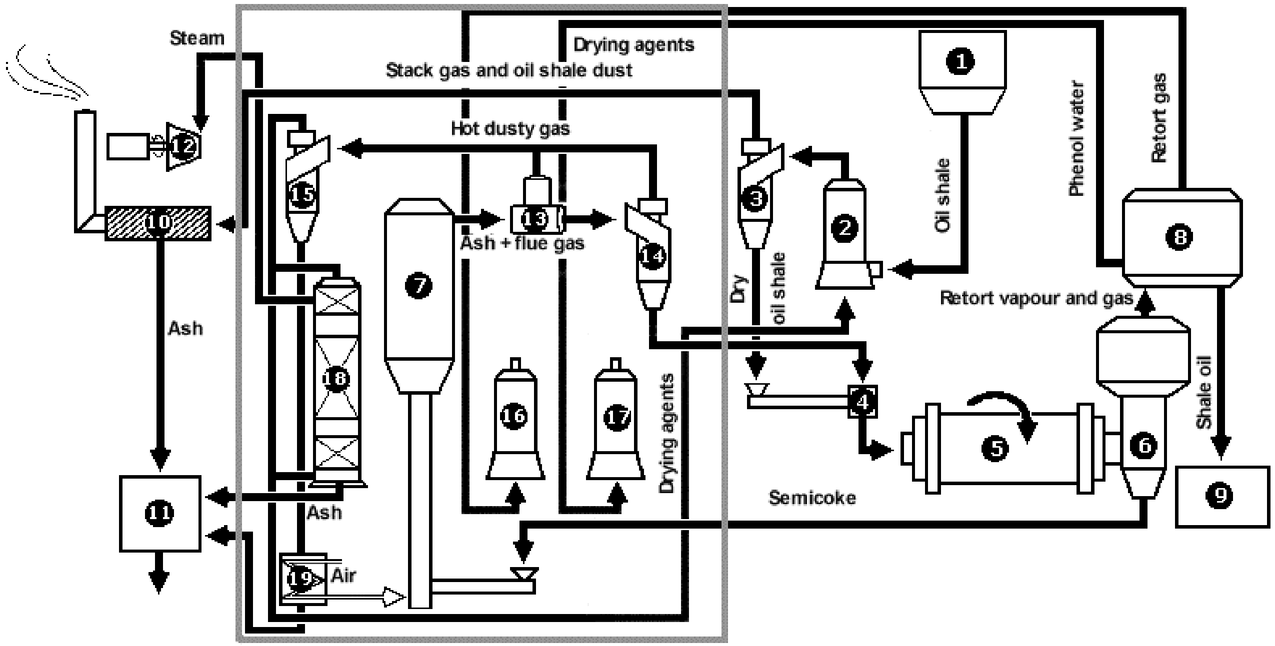

Fig. 4. Principal scheme of replacing part of SHC equipment with CFB boiler.

1 – oil shale storage, 2 – aero-fountain dryer, 3 – cyclone of dry oil shale, 4 – mixer of SHC and oil shale, 5 – rotating retort reactor, 6 – separator of semi-coke and oil vapour, 7 – aero-fountain furnace, 8 – condenser of oil vapour, 9 – storage of shale oil, 10 – electric precipitator with equipment for chemical purification of gases, 11 – slag and fly ash bunker, 12 – turbo-generator for power production, 13 – fraction separator of flue gas, 14 – separator of SHC, 15 – cyclone of hot gas, 16 – equipment for purification of retort gas from dust and sulphur compounds, 17 – equipment for utilization of phenol water formed in the retort process, 18 – utilization boiler using the heat of gases after the aero-fountain furnace, 19 – ash cooler.

The part of the technological scheme in the grey frame will be replaced with a circulating fluidised-bed boiler in the SPC technological scheme.

tion of a utilization boiler and an ash heat exchanger (pos. 18 and pos. 19 in Fig. 4), which in their initial performance did not operate as required. The new SPC technology also significantly improves environmental safety because after the CFB furnace there is no toxic waste.

As mentioned above, because of the lack of heating surfaces in the aero-fountain furnace in the SHC technological scheme (Fig. 2, pos. AFC), the combustion process must be implemented with the excess air factor at less than one to achieve the required temperature in the furnace. This in turn causes the presence of combustible matter in ash, and of uncompleted combustion gases (CO, H_2, CH_4 and others) and hydrogen sulphide in flue gas. These compounds influence the efficiency of the equipment and affect the environment as well. The ash formed under such conditions also contains calcium sulphide soluble in water.

The capacity of the gas cleaning equipment and also high temperature of flue gases do not enable sufficient cleaning of flue gases, particularly at start-up and shutdown regimes of SHC process. As a result great amounts of pollutants are emitted into the atmosphere (Table 1, column 3). Furthermore, a lean gas with high content of hydrogen sulphide forms at start-up and shutdown regimes. The gas is burned without cleaning in a chimney-flame tube of the retort equipment (columns 4 and 5 in Table 1).

Table 1. **The maximum values of emissions (mg/Nm^3) from various sources of pollution at Estonian Power Plant and Shale Oil Factory if flue gases contain 6% oxygen***

Pollutant	SHC processing technology				Estonian Power Plant	
	Main chimney of retorting equipment		Chimney of retorting equipment – flame tube			
	Steady-state operation regime	Start-up and shut-down regimes	Start-up and shut-down regimes	Burning of retorting gas in flame tube	Pulverised fuel-burning boilers	CFB boilers
Fly ash	840	16838			95-160	18
Sulphur dioxide	68	307		40921	1840-2140	15
Nitrogen oxides	320	44			275-280	118-119
Hydrogen sulphide	0	0	560			
Carbon oxide	19750	14740	45200			
Aliphatic hydro-carbons	1640	241	71500			
Phenols	125	3				
Ammonia	1	100				
Carbonyl sulphide	35	10				
Benzene	100	70				
Hydrogen chloride					23	

* Assessment of environmental impact of the Narva Power Plants development project. Report. August-October 2007, AF-ESTIVO Limited

In the case of the combined SHC and CFB technologies combustion occurs in the CFB boiler with the excess air factor exceeding one, which ensures the oxidising environment in the furnace. As a result, the ash practically does not contain combustible matter and flue gas does not contain uncompleted combustion products and hydrogen sulphide. Calcium sulphide does not form either. The concentration of sulphur dioxide in the flue gas is almost zero. The latter is absorbed by active calcium oxide in the furnace and the gas passes out of the CFB boiler.

Table 1 characterizes the amount of waste emitted into the atmosphere from various sources. A considerable reduction of emissions from shale oil production is expected in the case of the SPC technology because the amount of residual products will not differ from the amount of residual products in the case of oil shale burning in fluidised-bed boilers.

The SPC technological scheme is presented in Fig. 5. Oil shale is dried with hot flue gas in the dryer outside the drum reactor and separated from the drying agents in the cyclone separator. Dry oil shale is directed into the mixing chamber. Drying agents with oil shale dust are fed into the furnace of the CFB boiler.

The substantial feature of the SPC technology is the application of the ash circulating in the CFB boiler as a solid high-temperature heat carrier instead of using the high-temperature ash from the special semi-coke burning furnace for the same purpose. The ash from the CFB furnace is directed into the mixing chamber. Gaseous retort products are separated from the semi-coke in the separator. The semi-coke is then fed into the CFB boiler furnace.

In the case of the SPC technology high-calorific uncondensed retort gas is also directed into the furnace of the CFB boiler. So the unused heat of the oil shale retort process is released into the CFB boiler for generation of steam and used for production of electricity. This additional energy released in the CFB boiler constitutes 45% of the total energy content of oil shale (calorific value). According to preliminary calculations, the application of the SPC technology with a condensing turbine enables production of approximately 2–3 kWh electrical power per one kilogram of shale oil.

To make shale oil and power cogeneration more effective, it is rational that the thermal capacity of the CFB boiler should exceed the thermal capacity of the retort equipment determined on the basis of shale oil production ($1–Q_V/Q_T$). For this purpose raw oil shale from the fuel bunker must be directly burned in the CFB boiler for addition to semi-coke and high-calorific retort gas. The heat released by oil shale burning should be approximately equal to the thermal capacity of the retort equipment calculated on the basis of shale oil production. This criterion corresponds roughly to 50% of the boiler nominal capacity, the situation when the retort equipment is switched off. The relation between oil production and generated electricity depends on the total purpose of the SPC unit.

The implementation of the project improves the shale oil production process and ensures a more complete usage of the oil shale energy.

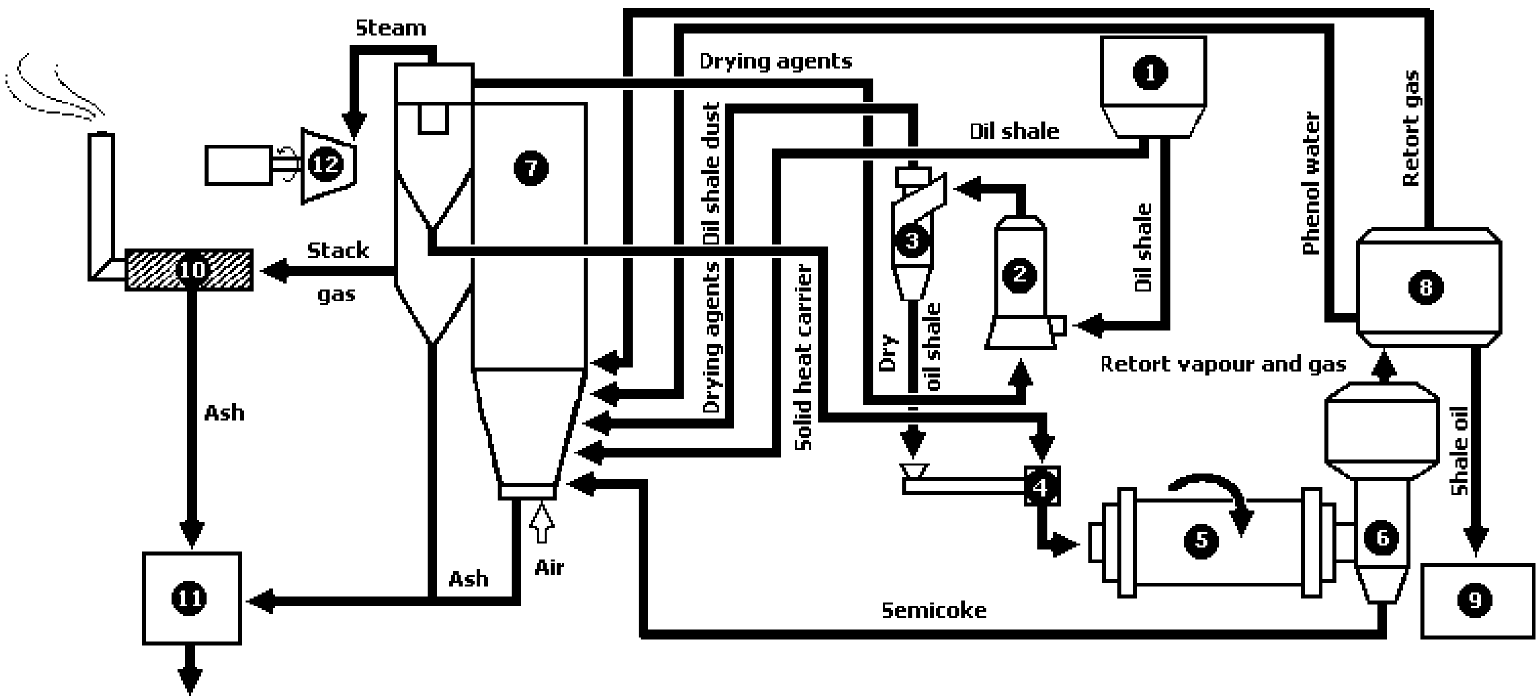

Fig. 5. SPC flow sheet.

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.

Description of the SPC process operation

Modern high-capacity power units are intended for non-stop operation. For example, the minimum start-up sequence duration of a CFB boiler (from 0% to 100% capacity) is about 8 hours. Thus it is unthinkable that malfunctions of shale oil production equipment could affect the electricity generation. According to the elaborated scheme, with direct oil shale feeding to the SPC boiler combustor, the system must guarantee continuous operation of boilers even in the case of an unexpected stop of oil production (for instance, due to technical problems).

The power unit connected to the oil production equipment could not be used for capacity regulation because it must first and foremost ensure that the oil production process is supplied with ash at the required temperature.

For the start-up of the oil retort equipment a sufficient amount of coarse-grade circulating ash is directed from the boiler together with the oil shale from bunker to the reactor located nearby (approximately 3 kilograms of ash per 1 kilogram of oil shale). The semi-coke from the reactor is directed uncooled (ca 480 °C) back to the CFB boiler.

Summary

1. The basic idea of shale oil and power cogeneration (SPC) is the application of the ash circulating in a CFB boiler as a solid high-temperature heat carrier, combining the CFB combustion technology with the retorting process. In the boiler, the heat for steam generation is obtained from burning of the retorting process products: semi-coke and high-calorific retort gas, but also direct burning of oil shale (not obligatory). The steam is applied for generation of electricity only, and, if needed, for cogeneration of electricity and heat or for technological purposes.
2. The SPC technology substantially simplifies the process scheme, compared with the individual systems, because the auxiliary equipment of the oil shale retorting unit (furnace for burning semi-coke, retort gas and phenol water, ash separators, recovery boiler, etc.) will become integral parts of the CFB boiler.
3. The SPC technology reduces the environmental impact of shale oil production because absolutely all emissions to the environment pass the CFB boiler where all processes occur in an oxidizing gaseous environment. As a result, there is practically no sulphur dioxide, hydrogen sulphide and carbon monoxide in the flue gas emitted into the environment. The ash contains no sulphide compounds.
4. The application of the SPC technology in one unit with a condensing turbine allows acquisition of approximately 2–2.5 kWh electrical power per one kilogram of shale oil. The implementation of the project enables improvement of the process of shale oil production and more effective usage of the oil shale energy.

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