THE MULTI-FUNCTIONAL ROLE OF HIGH-THROUGHPUT CFB'S IN THE OIL SHALE INDUSTRY

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Abstract – Limited availability of conventional petroleum resources and the world's growing demand for fuel and energy sources have brought about the need for development of efficient techniques to make use of fuel resources other than crude oil within the past decades. One of these resources is oil shale. With the aim of developing an energy-efficient and economically viable oil shale processing solution, Outotec and Eesti Energia have combined their competences in the fields of fluidized bed technology and solid heat carrier based oil winning. The developments achieved in the framework of this collaboration led to the Enefit280 oil winning plant, which is now operating in the eastern Estonian region of Auvere. The presented work provides a detailed overview of the Enefit280 process and the interdependence of its individual components. Special attention is paid to the multi-functional role of a circulating fluidized bed incinerator, which is operated at a solids feed rate of up to 840 tons per hour and is integrated into the process to provide heat for both the pyrolysis of oil shale and the generation of steam for power generation. Systematic implementation of the high-throughput CFB in the Enefit280 process allows for processing of oil shale at a total energy efficiency of 87%, which lifts the efficiency standard for oil shale processing plants to a high level.

INTRODUCTION

Advancing globalization brings people and markets closer together. As shown in a recent study, published by the World Bank (2016), the current phase of rapid globalization has led to shared prosperity and a significant reduction of global inequality since its beginning in the 1980s. Despite these indisputable benefits for the global community, the process of global integration also goes along with challenges in view of safeguarding the demand for energy and raw materials. For instance, the increasing demand for transportation has led to increasing fuel consumption (Engerer, 2015, U.S. Energy Information Administration, 2016). Moreover, the worldwide dissemination of electronic devices and the development of a global information society contribute to an increasing demand for energy (Fettweis, 2008). In order to be able to satisfy the increasing fuel and energy demand, intensive investigations for the identification of resources, which may serve as an alternative or as a supplement to conventional petroleum, have been initiated in several countries (Han et al., 2014, Jiang et al., 2007). At this, selected oil shale deposits in 33 different countries came into focus, the total of which corresponds to an estimated equivalent of 409 billion tons of in-situ shale oil (Dyni, 2006). According to Qian et al. (2008), this value exceeds the available amount of conventional crude oil (approx. 300 billion tons), which underlines the high relevance of oil shale as an energy source for the upcoming decades. To date, however, the costs for oil production from oil shale still exceed those for conventional crude oil extraction. Yet, shale oil production costs can well compete with those required for unconventional oil extraction methods such as deep-sea drilling and oil sands.

The term oil shale refers to a sedimentary material, which forms in a variety of depositional environments, e.g. freshwater and saline lakes, but also in the marine environment (Allix et al., 2011). The main constituents of oil shale are minerals, kerogen and water. The mineral composition may vary and typically includes silicates and different types of carbonates, e.g. calcite and dolomite (Allix et al., 2011). The target component of oil shale processing, however, consists in kerogen, which is a macromolecular mixture composed of carbon, hydrogen, sulfur and oxygen (Han et al., 2014). By exposing oil shale to elevated temperatures in the order of 500-530°C (Jiang, 2077) in an inert environment, kerogen degrades thermally to volatile hydrocarbons. This pyrolytic process step is typically carried out in a so called retort, a horizontal short rotary kiln or a vertical furnace. The evaporated hydrocarbons separate from the solid shale matrix and can be sent to a condensation unit subsequently to yield liquid and gaseous fuels.

The remaining solid shale matrix still contains residual carbon and is thus referred to as pyrolysis residue, spent shale or semicoke. The residual carbon material is composed of phenols, polycyclic and other hydrocarbons (Motlep et al., 2007), among which are soil and water pollutants. Disposal of these residues thus has a direct effect on the environmental impact of oil shale processing. On the one hand, the amount and type of residual carbon material is influenced by the conditions to which the oil shale is exposed during the pyrolysis step. On the other hand, also the origin of the oil shale has an impact. Han et al. (2014) provide an overview on the organic matter content and further characteristic properties of semicoke, which is produced from oil shale originating from different regions.

The brief introduction to the utilization of oil shale as an energy or fuel source, presented in the above paragraphs, shows that several challenges have to be met to make oil shale a viable alternative to crude oil. From an economic perspective, the production costs need to be kept low to achieve the ability to compete with conventional crude oil extraction. Key to this is the development of technologies, which allow for making resource- and energy-efficient use of oil shale. Another important aspect consists in the minimization of the environmental impact, caused by the production process and the generated by-products, e.g. semicoke. With that aim of meeting these requirements, Outotec and Eesti Energia have combined their competences in the fields of fluidized bed technology and solid heat carrier based oil winning. The developments achieved in the framework of this collaboration led to the Enefit280 oil winning plant, which was implemented in the eastern Estonian region of Auvere recently.

The following sections will provide a detailed overview of the Enefit280 process and the interdependence of its individual components. Special attention is paid to the multi-functional role of a high-throughput circulating fluidized bed incinerator, which is integrated into the process to provide heat for both the production of purified shale oil and the generation of electricity.

PROCESS DESCRIPTION

The raw oil shale, which serves as the feed material of the Enefit280 process, is derived from the Ordovician Kukersite deposit in northeastern Estonia. Before entering the Enefit280 (Fig. 1) the raw oil shale is crushed and screened to obtain particles smaller than 6 mm.

The design value of the raw oil shale feed rate amounts to 280 tons per hour. Typically, the moisture content of the raw oil shale feed is in the range of 9.0 - 12.7 wt.% (Runkel et al., 2014). In order to remove this initial moisture, the raw oil shale material is fed to a Venturi dryer (Fig. 1) in the first step of the Enefit280 process. As will be shown later on, the heat required for this drying step is provided by hot process gas, which is generated in subsequent operations of the Enefit280 process. Upon leaving the Venturi dryer, the dried oil shale is separated from the process gas by means of a cyclone and directed to the pyrolysis section (Fig. 1).

When entering the pyrolysis section, the dried oil shale is combined with hot ash, which is recirculated within the Enefit280 process and serves as a solid heat carrier to provide the energy required for pyrolysis. The pyrolysis step is carried out under inert conditions in a rotary kiln-type reactor. The reaction temperature is in the range of 480°C to 530°C. During pyrolysis, the kerogen contained in the dry oil shale is degraded thermally to volatile hydrocarbon species, which accumulate in the vapor phase. After passing the outlet of the retort, the enriched hydrocarbon vapor-gas mixture is separated from the remaining bulk mixture and subsequently directed to a condensation unit (Fig. 1).

Downstream processing in the condensation unit yields liquid and gaseous fuels, which constitute the primary target products of the Enefit280 process.

Pyrolysis does not allow for winning the entire hydrocarbon content of oil shale. A fraction of the initial organic carbon content remains in the solid shale particle matrix, which is called semicoke. For semicoke, derived from Estonian oil shale, Han et al. (2014) state an organic matter content in the range of 7.9 -9.1 wt%. To make further use of these carbon residuals, the solid bulk mixture obtained from the retort section is fed to a high-throughput circulating fluidized bed combustion unit (CFB, Fig. 1). The main incentive for choosing a circulating fluidized bed type combustor consists in the high particle mobility, which does not only allow for efficient contacting of gas and solids, but also enables the operator to adjust the combustion temperature with a homogeneous distribution throughout the entire combustion chamber. Typically, the temperatures within the CFB of the Enefit280 process are adjusted in the range of 750 - 800°C. Within the CFB, the mixture of semicoke particles and heat carrier ash is fluidized by air, which leads to the combustion of the organic carbon residuals contained in the semicoke.

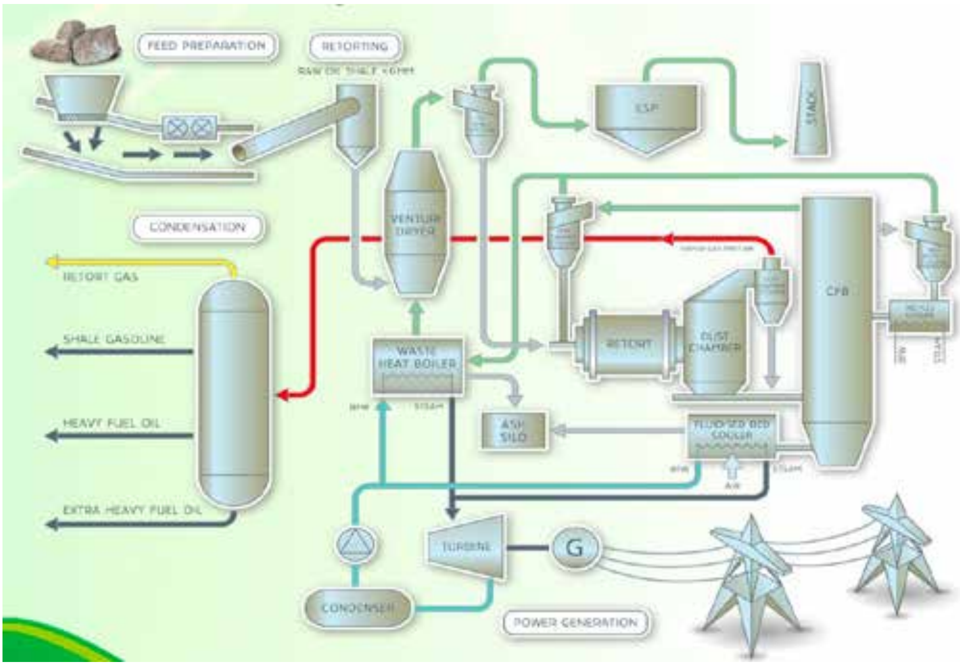

Fig. 1: Schematic representation of the process flows and unit operations in the Enefit280 process

Semicoke combustion serves multiple functions in the Enefit280 process. An overview on these functions is provided in Fig. 2. Moreover, a detailed description is presented in the following paragraphs:

1. *Generation of heat carrier ash for pyrolysis:*

   The unit operation with the largest energy demand of the Enefit280 process consists in the retort. In this, significant heat input is required to heat dry oil shale to pyrolysis temperature and to provide the enthalpy required for pyrolytic degradation of the contained kerogen to obtain volatile hydrocarbons. In order to satisfy the high energy demand of the retort, the Enefit280 process makes use of hot ash particles, so called solid heat carrier, originating from the CFB. Within the CFB, a significant fraction of the heat released by combustion of semicoke is transferred to the fluidized bulk material. By means of a cyclone separator, located at the top of the CFB (Fig. 1), hot ash particles can be withdrawn from the primary circulation loop of the CFB to serve as heat carrier particles. The particles withdrawn at the bottom of the so called heat carrier cyclone are directed to the inlet of the retort, where they are brought in contact with the dried oil shale feed. In this way, the heat released by combustion of organic carbon residuals in the depleted shale particles is used for heating up the dry oil shale feed.

2. *Utilization of excess heat for the production of electricity:*

   The heat released by combustion of semicoke within the CFB exceeds the amount of energy required for pyrolysis. Therefore, the excess heat contained in the flue gas and the entrained fine particles is used to produce superheated steam, which serves for the generation of electricity by means of a turbine (Fig. 1). On the one hand, excess heat is recovered from the fluidized solids. For this purpose a recycle cooler is installed in the primary circulation loop of the CFB. In addition to that, a fluidized bed cooler is installed in the ash discharge line of the CFB (Fig. 1). On the other hand, excess heat of the flue gas is utilized in the waste heat boiler upon leaving the CFB via the vortex finder of the cyclones.

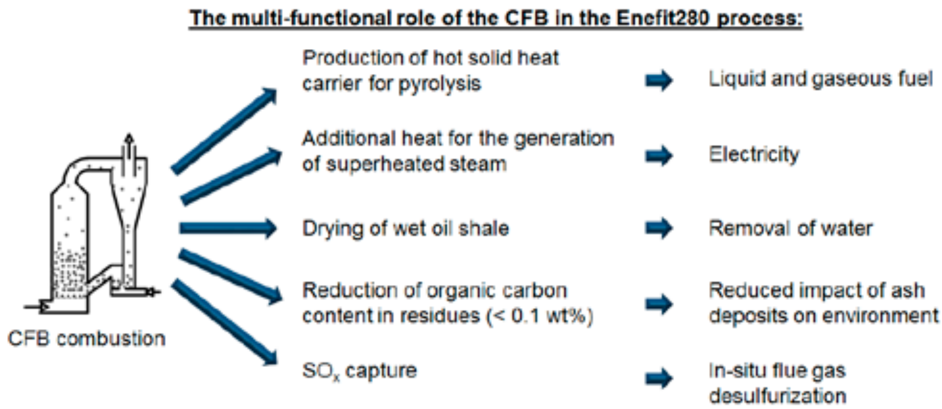

Fig. 2: The multi-functional role of the CFB combustion unit in the Enefit280 process

3. *Generation of hot gas for drying of raw oil shale:*

   After passing the waste heat boiler, the energy content of the flue gas is still sufficient for removal of the moisture in the raw oil shale feed entering the process. In order to achieve efficient heat transfer between gas and solids, the flue gas is brought in direct contact with the raw oil shale in a Venturi dryer (Fig. 1). Removal of water before pyrolysis is important as residual water reports to the condensation unit and has to be separated from the shale oil product, which is rather expensive.

4. *Reduction of the total organic carbon content (TOC) in solid waste products:*

   The solid by-product of the pyrolysis step, i.e. semicoke, contains residual organic material, which is hazardous to the environment. With the aim of minimizing the impact of oil shale processing on the environment, the residual organic carbon material of the solid waste products needs to be removed before disposal. This is achieved by adaptation of the combustion process within the CFB such that the TOC in the ash is less than 0.1 wt%.

5. *SO_x capture:*

   Oil shale typically contains a significant amount of sulfur. The exact amount varies with the geographical origin of the oil shale (Dyni, 2006, Knaus, 2010). The presence of sulfur in the combustion chamber bears the risk of forming sulfur oxides SO_x, which pollute the air and represent a major cause for the appearance of acid rain when emitted to the environment. In the combustion chamber of the CFB, however, SO_x reacts with calcium oxide, which is among the mineral constituents of the ash matrix, to form innocuous $CaSO_4$. Therefore, hardly any SO_x emissions occur and an additional flue gas desulfurization step is not required.

As mentioned earlier, the flue gas of the CFB is used to preheat and dry the wet oil shale, which is fed to the plant. After separation of the dried oil shale by means of a cyclone, the flue gas is passed on to an electrostatic precipitator (ESP). Here, the dust content is reduced to a level according to the emission permits and, subsequently, the cleaned flue gas is released to the environment via a stack.

FLUID-DYNAMIC BEHAVIOR OF THE CFB COMBUSTION UNIT

The solid feed material of the CFB is composed of mixture of semicoke and heat carrier ash, which is discharged from the retort. Owing to the removal of organic species from the initial oil shale feed by pyrolysis, the calorific value of the remaining semicoke is low compared to conventional fuels, fired in CFB combustors. Moreover, the fact that the semicoke particles are mixed with incombustible ash, which serves as a solid heat carrier for pyrolysis, reduces the calorific value of the solid feed material of the CFB to even lower values. With a value of approximately 0.6 – 0.8 MJ/kg, the calorific value of the solids fed to the CFB is in the order of 3 - 4% compared to bituminous coal (21.7 MJ/kg; Basu, 2006). In the CFB combustor of the Enefit280 oil winning plant, the heat contained in this low calorific feed is recovered.

The design of the combustion chamber of the CFB in the Enefit280 process allows for operation at a solid feed rate of up to 840 t/h. As the collection of solid heat carrier particles for use in other unit operations takes place below the cyclones at the top of the CFB, stable transport of solids vertically upwards within the combustion chamber is crucial. In order to get an insight into the flow condition, which prevails in the transport section of the combustion chamber, the fluid-dynamics in that plant section are modelled according to the steady-state model for heterogeneous fluid-solid flow according to Wirth (1990). This model is based on the force and mass balances in the regarded plant section and yields information on the prevailing gas-solid flow behavior under steady-state conditions. The result of these balances is typically displayed in a non-dimensional diagram (Fig. 3; Wirth, 1990). The following three non-dimensional quantities are the key-parameters of the steady-state diagram:

- *Particle Froude-number Fr_p:*

The particle Froude-number Fr_p is introduced as a non-dimensional measure for the superficial gas velocity u_0 in the transport section of combustion chamber (Wirth 1990). In the steady-state diagram shown in Fig. 3, the particle Froude-number is evaluated relatively to its design value $Fr_{p,design}$ (eq. 1) and plotted on the axis of abscissas.

$$Z = \frac{Fr_p}{Fr_{p,design}} \cdot 100\% = \frac{1}{Fr_{p,design}} \frac{u_0}{\sqrt{\frac{(\rho_s - \rho_g) g d_p}{\rho_g}}} \cdot 100\% \tag{1}$$

- *Non-dimensional pressure drop Π:*

The non-dimensional pressure drop is used as a measure for the force balances within the regarded system and is defined as shown in the following equation (Wirth, 1990). In the steady-state diagram, the non-dimensional pressure drop is displayed on the axis of ordinates.

$$\Pi = \frac{\Delta p}{(\rho_s - \rho_f)(1 - \varepsilon_{mf}) g \Delta L} \cdot 100\% \tag{2}$$

- *Volume flow ratio of solids and gas ξ:*

The volume flow ratio is defined as shown in eq. 3 (Wirth, 1990) and may be understood as measure for the transported solids mass flow rate $\dot{M}_S$ in the transport section of the combustion chamber at given values of Fr_p and Π. In the following, the volume flow ratio is evaluated relative to its design value $\xi_{max}(Fr_{p,design})$ and appears as parameter M for the array of curves in the steady-state diagram.

$$\xi = \frac{\dot{M}_s}{\dot{M}_g} \frac{\rho_g}{\rho_s (1 - \varepsilon_{mf})} \tag{3}$$

$$M = \frac{\xi}{\xi_{max,}(Fr_{p,design})} \tag{4}$$

The steady-state diagram, which results for the transport section of the CFB incinerator in the Enefit280 process, is displayed in Fig. 3. As indicated by the boundary line C, the upflow regime is divided into two different sections. In the flow regime located on the right hand side of the boundary line C, which is primarily characterized by increased particle Froude numbers, stable transport of solids vertically upwards occurs. In contrast to that, the flow regime on the left hand side of the boundary line C is characterized by comparably low particle Froude numbers. In this flow regime, the gas is saturated with solids and, consequently, axial disintegration of the flow field into a dense bottom section and a dilute transport section at the top takes place.

Aiming at stable conveying of solids to the top of the CFB, the operating point adjusted in the transport section of the combustion chamber needs to be located on the right side of the boundary line C. When operating at a particle Froude number, which corresponds to 100% of the design value, the resulting regime of stable operating points is indicated by the arrow in Fig. 3. The maximum of this range marks the transition point between the stable upflow regime and the saturated regime, in which axial disintegration of the flow field occurs. By iteration the value of the corresponding solids mass flow rate can be determined, which allows for stable transport of solids mass flow rates > 1000 t/h. In this way, the CFB guarantees sufficient supply of solid heat carrier for pyrolysis and the generation of superheated steam.

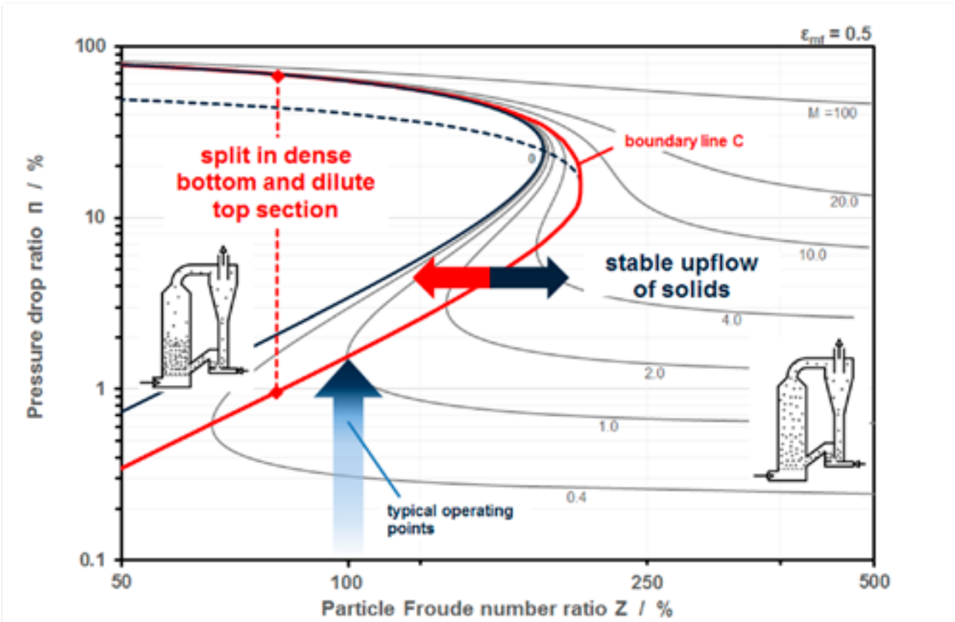

Fig. 3: Flow behavior of ash in the combustion chamber of CFB in the Enefit280 process; Model: Steady-state model for heterogeneous fluid-solid flow according to Wirth (1990)

SPECIFIC ENERGY BALANCE

The process description in the previous section shows that a major principle of the Enefit280 process consists in making effective use of the different constituents of oil shale. Therefore, the process does not only make use of organic carbon, which is accessible for producing fuel. It also uses the residual organic carbon, remaining after pyrolysis, to produce energy. By making efficient use of the residual carbon fraction, the energy demand for pyrolysis is covered completely. Moreover, excess heat is used to produce electricity. The scheme presented in Fig. 4 shows the specific energy balance of the process related to the production of one ton of shale oil.

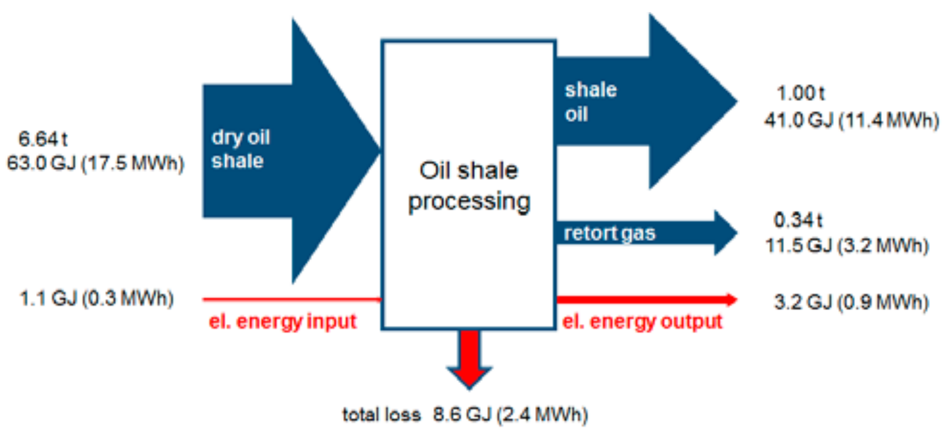

Fig. 4: Specific energy balance of the Enefit280 process for the production of 1.0 ton of shale oil; the width of the arrows represents the energy content of the individual process streams

As shown in the figure above, 6.64 t of dry oil shale are fed to the process to win one ton of shale oil. This is equivalent with a shale oil yield of 0.151 t of shale oil per ton of dry oil shale. Based on the calorific value of the produced shale oil, compared to that of the dry oil shale feed and the electrical energy input, the total efficiency related to oil is 64.7%. However, it is important to note that also 0.34 t of gaseous fuel are produced, which is not included in the above efficiency calculation.

The major fraction of the heat released by semicoke combustion is used for pyrolysis. Moreover, excess heat is utilized to produce superheated steam for the generation of electricity. With a specific energy output of 3.2 GJ per ton of shale oil (SO), the output of electrical energy exceeds the required electrical energy uptake of 1.1 GJ/t_{SO}. In view of an overall energy loss of 8.6 GJ/t_{SO}, the total energy efficiency of the Enefit280 process amounts to 86.6%.

CONCLUSION

In the presented elucidations, we show that the combination of a pyrolysis reactor with a circulating fluidized bed combustor, as implemented in the Enefit280 process, permits oil shale processing with a high degree of resource and energy efficiency. At this, a fundamental step consists in the generation of heat from organic carbon residuals, which are a solid by-product of the pyrolysis step and accrue in the form of semicoke. In the Enefit280 process, the heat generated from these organic carbon residuals is sufficient to satisfy the overall energy demand of the pyrolysis reactor. Excess heat is used for drying the raw oil shale feed, but also for the generation of electricity, which is fed into the local power network. In this way, an overall energy efficiency of 86.6% is achieved in the Enefit280 process. Besides its contribution to maximize the degree of efficiency, the combustion of carbon residuals also contributes to the minimization of the impact of oil shale processing on the environment. This is achieved by reducing the content of organic carbon residuals in the produced ash to a percentage of less than 0.1 wt%.

NOTATION

CFB	Circulating fluidized bed, -	Z	Froude number ratio, %
d_p	Particle diameter, m		
ESP	Electrostatic precipitator, -	ΔH	Height of the combustion chamber, m
Fr_p	Particle Froude number, -	Δp	Pressure drop, Pa
g	Gravitational constant, m/s²	ε	Volume fraction of the gaseous phase, -
M	Non-dimensional solids mass flow rate, -	$1-\varepsilon$	Volume fraction of the solid phase, -
$\dot{M}_g$	Gas mass flow rate, t/h	ε_{mf}	Bed voidage at minimum fluidization, -
$\dot{M}_s$	Solids mass flow rate, t/h	ξ	Volume flow ratio, -
SO	Shale oil, -	ρ_g	Gas density, kg/m³
TOC	Total organic carbon, -	ρ_s	Solids density, kg/m³
u_0	Superficial gas velocity, m/s	Π	Non-dimensional pressure drop, %

REFERENCES

Allix, P., Burnham, A., Fowler, T., Herron, M., Kleinberg, R., Symington, B. 2011. Coaxing Oil from Shale, Oilfield Review Winter 2010 22, 4-15.

Basu, P. 2006. Combustion and Gasification in Fluidized Beds, CRC-Press, Boca Raton, FL.

Dyni, J.R. 2006, Geology and resources of some world oil-shale deposits: U.S. Geological Survey Scientific Investigations Report 2005–5294, 42 p.

Engerer, H., Kunert, U. 2015. Fuel Consumption in Road Traffic – Gasoline and Diesel will Continue to Dominate in the Future of Road Transport, DIW Economic Bulletin 36, 469-478.

Fettweis, G., Zimmermann, E. 2008. ICT Energy Consumption – Trends and Challenges, 11th International Symposium on Wireless Personal Multimedia Communications 2008, Saariselkä, Finland.

Han, X.X., Kulaots, I., Jiang, X.M., Suuberg, E.M. 2014. Review of Oil Shale Semicoke and its Combustion Utilization, Fuel 126, 143-161.

Jiang, X.M., Han, X.X., Cui, Z.G. 2007. New Technology for the Comprehensive Utilization of Chinese Oil Shale Resources, Energy 32, 772-777.

Knaus, E., Killen, J., Biglarbigi, K., Crawford, P. 2010. An Overview of Oil Shale Resources, ACS Symposium Series: A Solution to the Liquid Fuel Dilemma, American Chemical Society, Washington, DC.

Motlep, R., Kirsimäe, K., Talviste, P., Puura, E., Jürgenson, J. 2007. Mineral Composition of Estonian Oil Shale Semi-Coke Sediments, Oil Shale 24, 405-422.

Qian, J.L., Wang, J.Q., Li, S.Y. 2008. World's Oil Shale Available Retorting Technologies and the Forecast of Shale Oil Production, 18th International Offshore and Polar Engineering Conference 2008, Vancouver, Canada, 19-20.

Runkel, M., Wirtz, A., Hammerschmidt, J., Pope, K. 2014. Fluidized Bed Applications for the Minerals Industry and Renewable Energy, 143rd Annual Meeting of the Minerals, Metals and Materials Society, San Diego, California.

U.S. Energy Information Administration. 2016. International Energy Outlook 2016 - With Projections to 2040, Office of Energy Analysis, U.S. Department of Energy, Washington, DC, DOE/EIA-0484(2016).

Wirth, K.-E. 1990. Zirkulierende Wirbelschichten – Strömungsmechanische Grundlagen, Anwendung in der Feuerungstechnik, Springer-Verlag, Berlin-Heidelberg.

World Bank. 2016. Poverty and Shared Prosperity 2016: Taking on Inequality. World Bank, Washington, DC, doi:10.1596/978-1-4648-0958-3.