Modelling of oil shale concentration processes in Estonian mines
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In Estonia, oil shale is used as a fuel for producing energy and as raw material for processing shale oil. Concentration plants at mines must guarantee required oil shale quality and quantity parameters. The processing rock material (run-of-mine) is the mineral composition, the quality of which depends on geological conditions and technology in mine. Mathematical description and data analysis are performed on working processes from working place (face) to a concentration plant: extraction, crushing, screening and concentration. A mathematical model for a concentration plant was created based on these studies. This model allows determining the optimum parameter kinds of trade oil shale and helps to design processing flow sheet.

Keywords: oil shale; heating value; waste limestone; concentration processes; flow sheet; model

Introduction

The oil shale industry of Estonia provides a significant contribution to the economy of the country. Oil shale is used as a fuel for producing energy and as a raw material for processing shale oil. More than 80% of electricity in Estonia comes from oil shale. The mining sector faces challenges to increase the output of mines, and at the same time to supply power and shale oil plants with suitable quality fuel and raw material.

The Estonian oil shale power plants use two heating technologies – pulverised firing and circulating fluidised bed combustion technology. These technologies require fuel grain size in the range (grade or class) 0–300 mm. The heating value must be no less than 8.4 MJ/kg. Shale oil generation has two technologies: processing lump oil shale in vertical retorts and pyrolysing fine oil shale with solid heat carrier. Heating value of lump oil shale (class 25–125 mm) must be no less than 11.4 MJ/kg. Raw material for solid heat carrier reactors is class 0–25 mm with heating value >8.4 MJ/kg. Concentration plants at mines must guarantee all kinds of saleable oil shale quality parameters in optimum ratios [1].

Feed of a concentration plant is run-of-mine (ROM), the quality of which depends on geological conditions of the mine field, and extraction technology including breakage, haulage, transporting and hoisting.
Geology and mining of the oil shale deposit in Estonia

Economically valuable oil shale reserves are situated in the north-eastern part of Estonia. The deposit extends some 30 km from north to south, and 200 km from west to east, respectively. The oil shale lies in the form of a flat deposit, having a small inclination (2–3 m per km) towards the south. Its depth varies from 5 to 150 m. The average thickness of mineable oil shale bed is quite constant, being 2.8 m. The resources of the Estonia deposit are estimated to be approximately four billion tonnes. The mineable oil shale bed consists of seven layers of oil shale (A, A’, B, C, D, E, and F₁) and five limestone interlayers (A/A’, A’/B, B/C, C/D and D/E) (Figure 1). The characteristics of various oil shale and limestone seams are different. They vary from field

Figure 1. The oil shale layer sequence in the Estonia oil shale deposit.
to field within the oil shale deposit. The average parameters of the mineable oil shale bed are presented in Table 1.

The heating value of oil shale layers with limestone concretions (nodules) is about 7.2–18.9 MJ/kg, which can vary considerably within the Estonian oil shale deposit and depends on the kerogen content. Average heating value of the bed decreases by 0.07 MJ/kg per one kilometre towards the south within the deposit. All the oil shale layers contain limestone lens-shaped nodules of size up to 15 cm. The heating value of limestone layers and nodules is up to 3 MJ/kg.

The compressive strength of oil shale is 20–40 MPa and that of limestone is 70–84 MPa. The volume density of oil shale in layers (composite of kukersite and limestone) is 1.22–1.72 Mg/m$^3$, limestone interlayers and nodules are 2.1–2.45 Mg/m$^3$. Strength and density rocks correlate with their heating values; therefore, it is possible to enrich the oil shale by gravity as well by mechanical methods.

Room-and-pillar technology with blasting is used in Estonian oil shale mines. The height of a room corresponds to the thickness of the mineable bed, 2.8 m or more [5]. The width of the rooms, 6–10 m, is determined by the stability of the immediate roof. The pillars cross-section, 50–60 m$^2$ in average, depends on the mining depth. The face advance rate by blasting works reached up to 4 m. Loading and transportation of blasted mined rock is carried out using load-haul-dump machines with a diesel drive.

**Concentration plant**

Enrichment of oil shale is a long-standing problem. In principle, it is a question of separating of limestone and oil shale from the ROM material. As mentioned above, physical and mechanical properties of oil shale and limestone are different. Therefore, it is possible to use separation by gravity methods, as well as by mechanical handling, for example, with a rotating drum.

**Table 1.** Representative parameters of the oil shale bed [2–4].

<table>
<thead>
<tr>
<th>Rock type</th>
<th>Layer and interlayer index</th>
<th>Heating value, MJ/kg</th>
<th>Organic matter (kerogen) content, %</th>
<th>Volume mass (specific gravity), Mg/m$^3$</th>
<th>Uniaxial compressive strength normal to the layering, MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kukersite in layers</td>
<td>F$_2$</td>
<td>6.67</td>
<td>18.9</td>
<td>1.72</td>
<td>37</td>
</tr>
<tr>
<td>(pure oil shale)</td>
<td>F$_1$</td>
<td>11.46</td>
<td>32.6</td>
<td>1.51</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>E</td>
<td>17.51</td>
<td>49.7</td>
<td>1.28</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>9.44</td>
<td>26.8</td>
<td>1.59</td>
<td>28</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>14.17</td>
<td>40.2</td>
<td>1.38</td>
<td>28</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>19.17</td>
<td>54.5</td>
<td>1.22</td>
<td>37</td>
</tr>
<tr>
<td></td>
<td>A$'$</td>
<td>7.47</td>
<td>21.2</td>
<td>1.42</td>
<td></td>
</tr>
<tr>
<td></td>
<td>A</td>
<td>15.12</td>
<td>42.9</td>
<td>1.37</td>
<td>28</td>
</tr>
<tr>
<td>Nodules in layers</td>
<td>F, E, C, B</td>
<td>2.92</td>
<td>8.3</td>
<td>2.10</td>
<td>75–80</td>
</tr>
<tr>
<td>Kerogenic limestone interlayers</td>
<td>E/F, D/E, B/C, A/A</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clayey limestone interlayers</td>
<td>C/D</td>
<td>0.63</td>
<td>1.8</td>
<td>2.45</td>
<td>84</td>
</tr>
<tr>
<td></td>
<td>A/B</td>
<td>1.25</td>
<td>3.6</td>
<td>2.45</td>
<td>69</td>
</tr>
</tbody>
</table>
It is a long-standing practice to prefer a heavy media (dense media) process [2,6,7]. The principal layout of concentration plants is shown in Figure 2.

The input of a concentration plant is ROM of size ≤300 mm. The first stage of the enrichment is sizing. Material is divided in two classes: 125–300 mm in first technological line and 0–125 mm in second technological line.

The first technological line. The feed of the first technological line is a coarse material, of the size 125–300 mm. Before the concentration, the feed will wash off and it forms slime with a solid component in the size of <2 mm. The products of processing are floating concentrate – lump oil shale (b) and sinking gangue (consists mostly of limestone) (c). The yield and heating value of the products depend on the density of the heavy medium. If it is commercially necessary, the concentrate of the first line is crushed to fine oil shale, up to 25 mm (a).

The second technological line. The secondary dry screening separates material into fine (0–25 mm) and coarse (25–125 mm) grain sizes. Fine oil shale (a) is used as a part of the final product. Until the present time, it has been possible to process only coarse material using a heavy medium. Coarse material will separate in heavy medium into trade product (b) and waste (c).

Dewatered slime (d) is added to commercial fine oil shale at a later phase. The trimming process will be used if the heating value of fine oil shale is less than suitable. The parameters of trade oil shale are usually not optimal. The aim of research is destined for the determination the optimal parameters of fine and lump oil shale.

Theoretical background

An extraction, crushing, sizing and concentration process of ROM determines the quality of oil shale production. These processes are, here, described by different functions and calculation methods.

Figure 2. Principal flow sheet of oil shale concentration.
Extraction and crushing

After blasting operation or crushing process, the mass distribution of rock material will be mathematically presented by a power function \[ y = A x^n; \quad 0 < y \leq 1 \] In this case, the function can be written as

\[ y = A x^n; \quad 0 < y \leq 1 \] (1)

where \( y \) – screenings part; \( x \) – grain size, mm; \( A \) and \( n \) – parameters of distribution: \( A \) – portion of fine material less than 1 mm in diameter (we call it, dust range), \( n \) – exponent, in our opinion – uniformity indicator.

Grain-size distribution curves of raw material and data analysis using different calculations are presented in Figure 3.

Publicly available spreadsheet applications provide tools for displaying equations and R-squared values on a chart, such as Microsoft Excel procedure – Data analysis ⇒ Trendline. However, the Excel procedure ‘Trendline’ uses logarithmic linearisation in case of a power equation. Our experience shows that logarithmic linearisation distorts approximation in different sections of the grain distribution (Figure 3). The Microsoft Excel procedure Solver (Generalised Reduced Gradient nonlinear optimisation code) gives a much better approximation.

Energy distribution, as well as mass distribution, of a rock material depends on grain size \[ 7 \]. Energy distribution after breakage and/or crushing process is described with the formula:

\[ q = Q_x \exp(-kx) + Q_{ROM} \] (2)

where: \( q \) – heating value of screenings; distribution parameters: \( Q_x \) – indicator of selective breaking; \( k \) – specific energy subsiding parameter; \( x \) – mesh, mm; \( Q_{ROM} \) – heating value of ROM. The energy distribution parameters are approximated using the Solver procedure. Figure 4 presents the heating distribution value depending on grain size from 0 to 125 mm. Heating value of different classes extracted and crushed rock can be quite accurately calculated by using this formula.

Figure 3. Mass distribution curves of a ROM using different calculation schemes.
Screening separates a flow of material into different classes. These are then processed to an intermediary product or a final product. Screening process changes this raw material distribution (Figure 5).

Screenings (underflow) mass distribution (class $A$–$B$ mm, if $A = 0$) is described by Formula (1) (Figure 3) and energy distribution by Formula (2) (Figure 4). The above-mentioned formulas are suitable to calculate mass and heating value of a sizing product using a variation of mesh sizes.

Determination of the screen overflow energy and mass calculations are somewhat complicated. Screen overflow (classes $B$–$C$) mass distribution can be described by a logistic function [4].

A generalised logistic curve can model the ‘S-shaped’ behaviour. It is used in modelling systems that saturate at large values of the argument. The initial stage of growth is approximately exponential; then, as saturation begins, the growth slows down, and when it reaches maturity, it stops altogether. The logistic function is the sigmoid curve with the equation:

$$y = \frac{1}{(1 \exp(b - ax))}$$

where $a$ and $b$ are constants; $x$ – grain size, mm (Figure 6).

The amount of screen overflow mass is easy to calculate with Formula (3). The energy calculation is restricted by lack of experimental data, and demands supplementary investigation.

Figure 4. Energy distribution of raw material after primary crushing in underground face.

Figure 5. A schematic layout of a screening process.
The screen overflow mass is presented by the following formula:

\[ \delta_{>x} = 1 - y_{<x} = 1 - Ax^n \]  

(4)

where \( \delta_{>x} \) — part of the mass overflow; \( y_{<x} \) — part of the underflow (Formula 1).

The values of energy calculation base on Formula 2. The energy of screen overflow is the difference between energy of extracted rock mass and screen underflow:

\[ E_{>x} = Q_{ROM} - (Q \exp(-kx) + Q_F)\delta_{>x} \]  

(5)

Concentration in heavy media

In Estonian oil shale mines, the concentration process of coarse material (oil shale and limestone mixture) in heavy medium is applicable. A schematic layout of concentration process is presented in Figure 7.

For modelling of concentration process in heavy media, the calculation scheme is based on the law of conservation of energy and principle of mass conservation.

The following system of linear equation is used:

\[ E = E_F + E_G \]  

(6)

and

\[ \delta = \delta_F + \delta_G \]  

(7)
where $E$, $E_F$ and $E_G$ – energy of feed, float (concentrate, lump oil shale) and sink (waste, gangue and mostly limestone); $\delta$, $\delta_F$ and $\delta_G$ – mass portion feed, float and sink.

Values of energy will be calculated by equations:

$$E = Q \delta, \quad E_G = Q_G \delta_G \quad \text{and} \quad E_F = Q_F \delta_F,$$

(8)

where $Q$, $Q_F$ and $Q_G$ – heating values of feed, float and sink.

Previous investigation has shown that an empirical relationship exists between heating values of waste, concentrate and ROM:

$$Q_F = 0.41(Q_G - Q_{ROM})$$

(9)

where $Q_{ROM}$ – heating value of extracted rock mass in face, it is the same as ROM.

It is known that the heating value of extracted rock mass is constant. If the heating value of lump oil shale increases the heating value of wastes increases too. Consequently, energy will be lost.

There are two possibilities for solving this system of a linear equation:

**The first option.** All the heating values of feed, float, sink and mass of feed are known. In this case, the above-mentioned system of two equations has two variables. It is easy to calculate the values of the two variables.

**The second option.** The heating value and mass of run of feed, heating value of float are known. Using Formula (8) it is possible to solve this system of equation. Investigation showed that in this case, the results are close to experimental data.

### Modelling

An oil shale concentration plant is a system of different processes. The main operations are dry screening and heavy media concentration. We describe them by simple mathematical formulas, which provide the opportunity to create an optimisation model.

**Screening operation**

Calculations are based on modified versions of Formulas (1) and (2).

$$\delta_{<x_i} = A x_i^n$$

(10)

and

$$Q_{<x_i} = Q_i \exp(-k x_i) + Q_{ROM}$$

(11)

where $\delta_{<x_i}$ is underflow ($\delta_{<x_i} \leq 1$); $Q_{<x_i}$ is the heating value of underflow; $x_i$ is the opening size of the sieve.

The mass and heating values of material flow are described by the following formulas:

$$\delta_{x_1...x_2} = \delta_{<x_2} - \delta_{<x_1}$$

(12)

$$Q_{x_1...x_2} = (Q_{<x_2} \delta_{<x_2} - Q_{<x_1} \delta_{<x_1}) / \delta_{x_1...x_2}$$

(13)
where $\delta_{x_1 \ldots x_2}$ is the mass between sieve opening sizes $x_1$ and $x_2$ (yield of class $x_1 \ldots x_2$); $Q_{x_1 \ldots x_2}$ is the heating value of class $x_1 \ldots x_2$.

Graphical interpretation of Formulas (12) and (13) is given in Figures 8 and 9.

Typical screening unit operation is presented in Figure 10.

The input of screening unit is ROM. The output is yield and heating values of class $x_1 \ldots x_2$. Sieve opening sizes $(x_1, x_2)$ determine the quality parameters of the output production. The sieve opening sizes are the variables of optimisation between predetermined constraints.

**Concentration operation**

Concentration in heavy media is described by Formulas (6)–(9). Modified formulas for typical concentration unit operation are the following:

$$Q_{gi} = 0.41(Q_{Fi} - Q_{ROM})$$  \hspace{1cm} (14)

$$\delta_{Fi} = \delta(Q - Q_{gi})/(Q_{Fi} - Q_{gi})$$  \hspace{1cm} (15)

$$\delta_{gi} = \delta(Q_{Fi} - Q)/(Q_{Fi} - Q_{gi})$$  \hspace{1cm} (16)

The heating value of float $Q_{Fi}$ is required by the consumer (Figure 11).

Feed of concentration unit operation is the output from screening. The output of the concentration unit is coarse oil shale and tailings. Lower limit of heating value of coarse concentrate (common term – lump oil shale) is given in the optimising process, determining the density of heavy medium.

**Target of optimisation and subject to restrictions**

Optimisation plans of the concentration plant have two possible goals (targets):

- (1) Maximum concentrate yield with heating value more than 11.4 MJ/kg
- (2) Maximum trade oil shale mass output with heating value more than 8.4 MJ/kg

![Figure 8. Graphical representation of the calculations of mass (class $x_1 \ldots x_2$).](image-url)
The first goal corresponds to the needs for oil processing in vertical generators. Accordingly, the target is

$$\delta_{F_i} \rightarrow \text{max}$$

Subject to the constraints:

1. Primary screening sieve opening size constraint: $125 \leq x_1 \leq 150$ mm.
2. Secondary screening sieve opening size constraint: $25 \leq x_3 \leq 40$ mm.
3. Lump oil shale heating value constraint: $Q_{F2} \geq 11.4$ MJ/kg.
4. Fine oil shale heating value constraint: $Q \geq 8.4$ MJ/kg.

The second goal corresponds to the needs of power stations as well as of oil processing plants with solid heat carriers.

$$\delta_{F_i} + \delta_{x_1...x_2} \rightarrow \text{max}$$
In this case, subject to the constraints are:

1. Primary screening sieve opening size constraint: $125 \leq x_1 \leq 150$ mm
2. Secondary screening sieve opening size constraint: $25 \leq x_3 \leq 40$ mm
3. Trade oil shale heating value constraint: $Q \geq 8.4$ MJ/kg

**Concentration plant model**

An optimal flow sheet for a concentration plant is created using Microsoft Office Excel. It is the basis on the above-mentioned algorithms for calculating the parameters of rock mass extraction, crushing, screening and concentration process, as shown in (Figure 12).

Figure 12. Schematic layout of the model for a concentration plant.
The model based on a concentration plant is presented in Figure 2. General parameters of flow sheets (input and output) in screening and concentration operations are shown: masses and heating values. Input of the optimiser is the feedback from trade oil shale parameters. Optimiser can change the sieve opening sizes and trade oil shale heating values in given restricted ranges. A procedure called Solver in Microsoft Excel suits best for the optimisation.

**Modelling results and discussion**

Mostly, the ROM size is $\leq 300$ mm and heating value is not less than 6.5 MJ/kg. In the first stage of the enrichment process, screening for separating feed is divided in two classes: 125–300 mm (the first technological line) and 0–125 mm (the second technological line).

*The first technological line.* Coarse size of 125–300 mm makes 20% from the total value with energy distribution with heating value 5.3 MJ/kg. Before concentration, it is washed and forms about 1% slime (with solid class 0–2 mm) by a heating value of 7.5 MJ/kg. The output of concentration is lump oil shale and lump limestone as waste. Heating value of lump oil shale is determined by the conditions of sale. Waste has heating value $< 2$ MJ/kg.

*The second technological line.* The secondary screening separates feed from fine 0–25 to 40 mm and coarse 25–40 to 125 mm size classes. Fine grain size will make about 41% of the total value with heating value of about 8 MJ/kg.

Two concentration plants flow sheets with several targets were optimised (Table 2).

**Conclusions and recommendations**

(1) In Estonian oil shale mines, the full-face mining technology with blasting is used. ROM is a mixture of oil shale and limestone, which demands processing in concentration plants. Due to the different properties of ROM, it is necessary to perform optimisation of the processes in a concentration plant.

(2) Analysis and mathematical description of the processes in concentration plants is done. It is shown that extraction and crushing processes can be presented by a power function (Gates–Gaudin–Schumann model), and screening processes

**Table 2. Examples of optimised products plan for concentration plants.**

<table>
<thead>
<tr>
<th></th>
<th>Ojamaa mine [8]</th>
<th>Estonia mine</th>
</tr>
</thead>
<tbody>
<tr>
<td>ROM heating value, MJ/kg</td>
<td>9.11</td>
<td>6.53</td>
</tr>
<tr>
<td>Optimising target</td>
<td>Max lump oil shale</td>
<td>Max lump oil shale</td>
</tr>
<tr>
<td>Optimised yield at ROM, %</td>
<td>Fine oil shale 32</td>
<td>49</td>
</tr>
<tr>
<td></td>
<td>Slime 2</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Lump oil shale 38</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>Waste 28</td>
<td>36</td>
</tr>
<tr>
<td>Heating value</td>
<td>Fine oil shale 8.4</td>
<td>8.4</td>
</tr>
<tr>
<td></td>
<td>Lump oil shale 12</td>
<td>11.4</td>
</tr>
<tr>
<td>Recovery (mass), %</td>
<td>70</td>
<td>63</td>
</tr>
<tr>
<td>Output–input energy ratio, %</td>
<td>94</td>
<td>89</td>
</tr>
</tbody>
</table>
by a logistic function. Modelling of concentration processes in heavy media is based on the law of conservation of energy and principle of mass conservation.

(3) An optimal flow sheet for a concentration plant is created, using available calculating programme. It is based on the developed algorithms for calculating parameters of different processes in a concentration plant. Maximum mass output and maximum oil shale yield determine the target of optimisation. This target is reached by changing mesh opening sizes.

(4) Two concentration plant flow sheets with several targets were optimised. A developed model gives good results. It is recommended to adjust flow sheets of working and designed concentration plants in oil shale mines of Estonia.

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Note
1. Also know as Gates–Gaudin–Schuhmann model.

References