Oil Shale, 2019, Vol. 36, No. 1, pp. 32–42
doi: https://doi.org/10.3176/oil.2019.1.03
ISSN 0208-189X

EXPERIMENTAL STUDIES ON CUTTING OIL SHALE BY HIGH-PRESSURE WATER JETS

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Abstract. *Oil shale is one of the most promising replacements for traditional energy resources. Its total reserves are enormous, and, moreover, they are widespread. This makes shale oil insensitive to problems of individual suppliers. A lot of countries, which lack traditional energy sources for their development, are conducting investigations in the field of an increase of the effectiveness of oil shale as a substitute for oil and gas. These studies are mostly concerned with processing of oil shale. At this, economic and ecological effects could also be reached upon extraction. This paper deals with experimental studies on cutting oil shale by high-pressure water jets. The outcome was establishing a generalized equation for calculating the efficiency of oil shale cutting by high-pressure water jets and equations for estimating rational values of hydraulic parameters such as water pressure and diameter of the nozzle orifice as well as rational value of the traverse speed.*

Keywords: *oil shale cutting, waterjet technology, hydraulic parameters, high-pressure water jet.*

1. Introduction

As petroleum and gas are natural resources that are being rapidly consumed, which can lead in the nearest future to the impossibility to meet the ongoing and increasing demands of the civilization for energy, there are made great efforts worldwide to seek possible substitutes for them [1]. One of the most potential replacements for traditional hydrocarbon resources is shale oil due to its enormous reserves worldwide [2, 3]. Another important issue related to oil shale is the distribution of its deposits widely around the world, namely in the United States, Russia, China, Brazil, Australia, and many others [2, 3].

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At this, a lot of new deposits of this mineral have been discovered recently. This makes the supply of shale oil stable to political or economic problems in distinct countries or regions. This is vital for the sustainable development of countries dependent on external suppliers of energy resources. For example, China, which lacks hydrocarbon resources needed to its tremendous economic growth, is the biggest unconventional shale oil producer [4]. Estonia pretends to have the largest oil shale industry active today [5]. Oil shale industry is considered as a key to energy independence in China, Estonia, Turkey, Jordan, and some others countries [2, 5].

Oil shale industry needs innovations to strengthen its positions as an equitable energy source supplier. Of course, R&D programs for this are being conducted in most of the countries listed in the first paragraph. These programs investigate mainly methods for increasing calorific value, reducing harmful impurities and improving liquefaction efficiency, as well as deal with problems of gas generation, combustion products processing and their industrial use, and other issues related to processing of excavated shale [6–9]. At this, there are significantly fewer studies on the development of mining methods increasing extraction efficiency and being safe and environment-friendly as well.

An important issue related to excavation of oil shale is the percentage of coarse material with a fraction of 25–600 mm, which is a significant factor for the further processing of oil shale as an energy resource. As was previously established for hydro-mechanical and hydraulic cutting of coal [10], the use of high-pressure water jets for rock cutting allows an enhancement of the quality of the excavated mineral resource due to the higher percentage of +25 fractions. Along with this it also increases excavation productivity several times and improves working conditions due to explosion, intrinsic and fire safety. At the same time, we do not know any specific complex research on the excavation of oil shale with the use of waterjet technologies. This limits possibilities of their introduction into the industry. Thus, a study on oil shale cutting by high-pressure water jets is needed.

2. Methodology

Based on the accumulated experience of cutting various rocks with the use of waterjet technologies [11], we can assume that the main factors influencing cutting efficiency of oil shale are:

- physical and mechanical properties of oil shale, which are mainly characterized by strength (resistivity of a material to destruction);
- hydraulic parameters of the cutting equipment such as the water pressure and the diameter of the nozzle orifice;
- some technical aspects such as the traverse speed of the jet (speed of jet movement relative to surface), the distance to rock surface, and the cutting angle.

As to the physical and mechanical properties, taking into account known studies [12, 13] we can reasonably argue that unconfined (also known as uniaxial) compressive strength is the most appropriate parameter to describe the strength of oil shale.

Earlier, when cutting coal and rocks by water jets, it was established that the highest effectiveness was achieved with the use of the vertical orientation of the jet relative to the surface of rock [14, 15]. Thus, we investigate the destruction of oil shale in this study at an angle of 90 degrees.

To estimate the efficiency of oil shale cutting by high-pressure water jets, the depth of cut is chosen. The dependence of this value on the above-listed parameters obeys the following general pattern:

$$h = f\left(\sigma_c,\ P_0, d_0, u, l_0\right), \qquad (1)$$

where σ_c is the uniaxial compressive strength; P_0 is the water pressure; d_0 is the diameter of the nozzle orifice; u is the traverse speed; l_0 is the distance to rock surface.

The study of the process of interaction of high-speed water jet with oil shale is a very complex theoretical task. The difficulty is due to the unexplored cutting process with such a tool, and, therefore, the lack of sufficient information about the mechanism of interaction of the jet with shale. That is why the study of the cutting process of oil shale by high-speed water jet was performed using the experimental method with the following analysis of the experimental data, applying the theory of probability and mathematical statistics.

To conduct experimental studies on the influence of the main factors determining the process of destruction of oil shale by high-pressure water jets, a special stand was designed. The scheme of the stand is shown in Figure 1 and the technical characteristics are given Table 1.

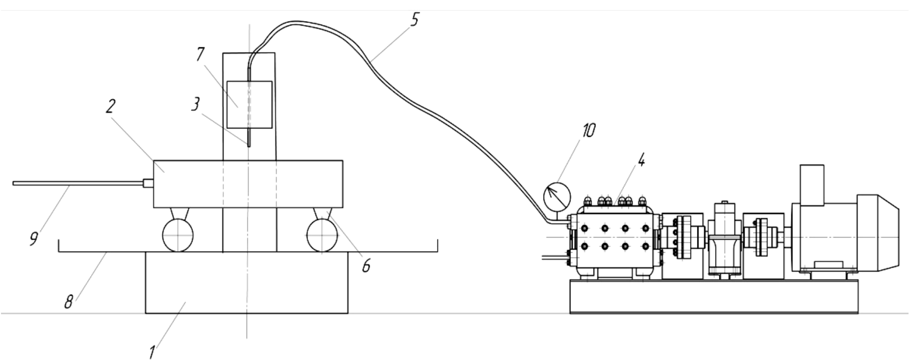

Fig. 1. Scheme of testing equipment: *1* – the frame; *2* – the oil shale sample; *3* – the jet forming device; *4* – the pump; *5* – the high pressure hose; *6* – the movable table; *7* – the holder; *8* – the guiding units; *9* – the cable; *10* – the manometer.

Table 1. Technical characteristics of testing equipment

Parameter	Value
Water pressure, MPa	120
Pump flow rate, l/min	10
Distance to oil shale sample surface, mm	No more than 15–25
Traverse speed, m/s	Up to 0.4

As previously mentioned, experiments were carried out at the vertical orientation of the water jet relative to the surface of the oil shale sample. The distance between each cut was at least three values of the cut width. After processing each individual layer, the surface of the block was cleaned to the depth of the cuts formed. The distance from the jet forming device to the oil shale sample surface did not exceed the length of the start section of jets, which in the study was in the range of 15–25 mm. The depth of cut was measured by a caliper at not less than 5 points along its length, and the average value was recorded. This is shown in Figure 2.

Oil shale from the Ojamaa mine, Estonia was subjected to cutting. The samples were obtained by the drill-and-blast method from layer E in November 2013. Table 2 gives the strength of the samples cut. These values were obtained by the ISRM-suggested method [16]. The samples had a nearly perfect rectangular form with dimensions of 500 × 500 × 300 mm.

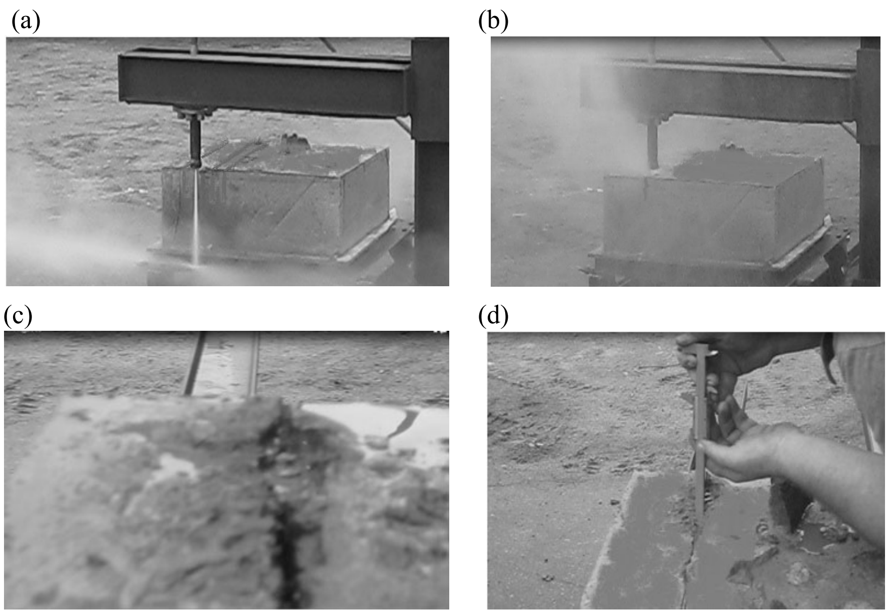

Fig. 2. Oil shale cutting by high-pressure water jets: a) before cutting; b) cutting; c) cut; d) measurement of the depth of cut.

Table 2. Strength of oil shale samples

Sample No	σ_c, MPa	Variation, %
1	11.1	19.2
2	16.3	6.6
3	24.6	18.3
4	32.2	4.8
5	62.3	7.8

An important issue regarding rock cutting is power requirements of equipment. To estimate the hydraulic power of the testing equipment for oil shale cutting we used the following equation:

$$N = 0.0351 \cdot \mu \cdot d_0^2 \cdot P_0^{1.5}, \tag{2}$$

where N is the hydraulic power, W; μ is the coefficient for the velocity loss due to friction between the water flow and the orifice wall; d_0 is the diameter of the nozzle orifice, mm; P_0 is the water pressure, Pa.

The constant in Equation (2) was obtained on an assumption that the density of water was 1000 kg/m^3.

3. Results of experimental studies

3.1. Influence of the strength of oil shale on cutting efficiency

Experimental studies to determine the effect of oil shale strength on the depth of cut were carried out on samples of oil shale with σ_c = 11.1, 24.6 and 62.3 MPa at the traverse speed u = 0.35 m/s. The experiments were carried out at a water pressure P_0 = 10, 30, 50 and 70 MPa, and the diameter of the nozzle orifice d_0 = 2 mm.

Table 3 presents the results of the effectiveness of oil shale cutting by high-pressure water jets.

Table 3. Influence of oil shale strength on the efficiency of cutting by high-pressure water jets

Uniaxial compressive strength σ_c, MPa	Water pressure P_0, MPa	Depth of cut h, mm	Hydraulic power N, kW
11.1	10	79	3.3
24.6	10	54	3.3
62.3	10	29	3.3
11.1	30	145	17.3
24.6	30	100	17.3
62.3	30	72	17.3
11.1	50	167	37.2
24.6	50	120	37.2
62.3	50	85	37.2
11.1	70	117	61.7
24,6	70	118	61.7
62.3	70	90	61.7

The growth of water pressure leads to a linear increase of the effectiveness of cutting. For stronger oil shale samples the depth of cut is smaller, disregarding the water pressure. This means that there is no rational value of the ratio of water pressure to oil shale strength at which less energy would be consumed or cutting would be more effective.

3.2. Influence of the hydraulic parameters on cutting efficiency

Experimental studies to determine the effect of water pressure and the diameter of the nozzle orifice (hydraulic parameters) on the depth of cut were carried out on samples of oil shale with σ_c = 11.1 MPa at the traverse speed u = 0.35 m/s. The experiments were carried out at a water pressure P_0 = 10, 20, 30, 40; 50, 60 and 70 MPa, and the diameter of the nozzle orifice d_0 = 2.0, 2.5 and 3.0 mm.

Table 4 shows the dependence of the effectiveness of oil shale cutting by high-pressure water jets on hydraulic parameters.

Table 4. Influence of hydraulic parameters on cutting efficiency

Water pressure P_0, MPa	Diameter of orifice nozzle d_0, mm	Depth of cut h, mm	Hydraulic power N, kW
10	2.0	11	3.3
10	2.5	12	5.2
10	3.0	16	7.5
20	2.0	41	9.4
20	2.5	37	14.7
20	3.0	50	21.2
30	2.0	60	17.3
30	2.5	70	27.0
30	3.0	90	38.9
40	2.0	80	26.6
40	2.5	100	41.6
40	3.0	120	59.9
50	2.0	92	37.2
50	2.5	118	58.2
50	3.0	162	83.8
60	2.0	113	48.9
60	2.5	158	76.5
60	3.0	185	110.1
70	2.0	155	61.7
70	2.5	172	96.4

The increase of water pressure and the diameter of the nozzle orifice leads to the growth of the depth of cut, which is explained by the higher hydraulic power. The relation of the hydraulic power to the volume of destructed rock gives us a specific energy of oil shale cutting by high-pressure water jets. It is obvious that less specific energy for destruction means a rational mode of cutting. The conducted experimental study allows us to estimate the rational values of the hydraulic parameters as represented by Equation (3):

$$P_0 = 72.63 \cdot d_0^{-1.08}. \quad (3)$$

The coefficient of determination R^2 of Equation (3) is equal to 0.94.

3.3. Influence of the traverse speed on cutting efficiency

In comparison with a stationary water jet forming a cone funnel, a movable jet could increase the productivity of cutting significantly as the moving water jet forms a slit, and the hydraulic cushion is eliminated since the waste water will not accumulate at the bottom, but will freely flow across the slit [17]. Besides, the formed slit is an auxiliary surface attenuation plane. The establishment of a rational traverse speed is also a prerequisite for a scientifically justified choice of a cutterhead drive, which uses a high-speed water jet as a rock cutting tool.

Experimental studies to determine the effect of the traverse speed on the depth of cut were carried out on samples of oil shale with σ_c = 26.4 MPa at the traverse speed u = 0.03, 0.1, 0.25 and 0.35 m/s. The experiments were carried out at a water pressure P_0 = 50 and 70 MPa, and the diameter of the nozzle orifice d_0 = 2.0, 2.5 and 3.0 mm.

Table 5 shows the dependence of the effectiveness of oil shale cutting by high-pressure water jets on the hydraulic parameters.

Table 5. Influence of the traverse speed on cutting efficiency

Traverse speed u, m/s	Water pressure P_0, MPa	Diameter of nozzle orifice d_0, mm	Depth of cut h, mm	Hyfraulic power N, kW
0.03	70	3.0	200	138.8
0.03	50	3.0	186	83.8
0.03	70	2.5	154	96.4
0.03	50	2.5	143	58.2
0.03	70	2.0	118	61.7
0.03	50	2.0	120	37.2
0.1	70	3.0	179	138.8
0.1	50	3.0	164	83.8
0.1	70	2.5	138	96.4
0.1	50	2.5	124	58.2
0.1	70	2.0	105	61.7
0.1	50	2.0	99	37.2
0.25	70	3.0	126	138.8
0.25	50	3.0	111	83.8
0.25	70	2.5	96	96.4
0.25	50	2.5	89	58.2
0.25	70	2.0	73	61.7
0.25	50	2.0	67	37.2
0.35	70	3.0	95	138.8
0.35	50	3.0	79	83.8
0.35	70	2.5	67	96.4
0.35	50	2.5	58	58.2
0.35	70	2.0	41	61.7
0.35	50	2.0	35	37.2

As seen from Table 5, with the growth of the traverse speed the depth of cut almost linearly decreases. Qualitatively this behavior is irrespective of water pressure and diameter of the nozzle orifice. At this, with higher values of both parameters the effectiveness of cutting increases for each value of the traverse speed. So, the degree of the influence of the traverse speed on the investigated hydraulic parameters of the jet is the same.

Table 6 presents rational values of the traverse speed for each set of hydraulic parameters.

Table 6. Dependence of the rational value of the traverse speed on the hydraulic parameters

Water pressure P_0, MPa	Diameter of nozzle orifice d_0, mm	Rational value of the traverse speed u, m/s
50	2.0	0.237
70	2.0	0.248
50	2.5	0.275
70	2.5	0.290
50	3.0	0.294
70	3.0	0.322

Using the multiple regression method for the data from Table 6, we obtained an equation for rational traverse speed:

$$u = 0.075 \cdot P_0^{0.19} \cdot d_0^{0.59} . \tag{4}$$

The coefficient of determination R^2 for Equation (4) is equal to 0.98.

4. Discussion

Although the results obtained in section 3 of this paper are quite useful, they are not united by a common equation. So, they cannot show a full distinct picture of oil shale cutting by high-pressure water jets. In order to generalize all the experimental data from section 3, let us adopt similarity and dimension analysis methods. For this we should use the π-theorem, which states that any equation relating to N physical quantities, among which K quantities have independent dimensions, can be transformed into an equation connecting N-K dimensionless complexes and simplexes composed of these quantities, which are criteria of similarity [18].

Equation (2) consists of six parameters describing rock cutting by pulsating jets. At this, the distance to rock surface was invariant during experimental studies; therefore, it should not be considered. Instead, we can include such an important parameter as the velocity of water jet. The ratio of the traverse speed to this parameter is a dimensionless simplex of a velocity similarity. To estimate the velocity of water jet v_0 is possible using equation (5) [19]:

$$v_0 = \mu \cdot \sqrt{\frac{2 \cdot P_0}{\rho}}, \tag{5}$$

where ρ is the water density (its value is usually 1000 kg/m^3).

In the M-L-T system (Mass-Length-Time) these parameters have the following dimensions:

$$[h] = L; \quad [d_0] = L; \quad [v_0] = L \cdot T^{-1}; \quad [u] = L \cdot T^{-1}; \quad [P_0] = M \cdot L^{-1} \cdot T^{-2};$$
$$[\sigma_c] = M \cdot L^{-1} \cdot T^{-2}.$$

As quantities with independent dimensions we take P_0, d_0 and u. The matrix of their dimensions consists of three lines, where each element of the line is an indicator of the degree of dimensionality of mass, length and time, respectively, of the values taken as the basis. Thus,

$$D = \begin{vmatrix} 1 & -1 & -2 \\ 0 & 1 & 0 \\ 0 & 1 & -1 \end{vmatrix} = -1 \neq 0. \tag{6}$$

As the determinant of the dimension matrix D is not equal to zero, dimensions of P_0, d_0 and u are independent. Therefore, according to the π-theorem, the generalized equation of oil shale cutting by high-pressure water jets includes three criteria of similarity. The next step is to establish the exact form for the generalized equation. Table 7 summarizes experimental data used in this study for estimating coefficients in the regression model for this.

As a result of the processing of experimental data and in accordance with the similarity and dimension analysis methods, the generalized equation for calculating the oil shale cutting efficiency by high-pressure water jets will have the following form:

$$\frac{h}{d_0} = 15.7 \cdot \left(\frac{P_0}{\sigma_c}\right)^{1.53} \cdot \left(\frac{u}{v_0}\right)^{-0.34}. \tag{7}$$

The coefficient of determination R^2 of Equation (7) is equal to 0.93.

Table 7. Summarized experimental data

Parameter	Ranges of parameter values
Water pressure P_0, MPa	10–70
Diameter of nozzle orifice d_0, mm	2.0–3.0
Traverse speed u, m/s	0.03–0.35
Velocity of water jet v_0, m/s	106.1–259.8
Unconfined compressive strength σ_c, MPa	11.1–62.3

5. Conclusions

As a result of the experimental studies, the problem of obtaining a generalized equation for calculating the efficiency of oil shale cutting by high-pressure water jets is solved. For a wide variety of special tasks relating to the justification of equipment parameters, the equations for estimating rational values of hydraulic parameters such as water pressure and the diameter of the nozzle orifice as well as a rational value of the traverse speed are also useful.

Further investigations should allow elaborating a method or a group of methods for the designing of equipment for oil shale excavation with the use of high-pressure water jets.

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Presented by E. Reinsalu and A. Siirde
Received July 3, 2018