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EXPERIMENTAL STUDY OF THE THERMAL REAMING OF THE BOREHOLE BY AXIAL PLASMATRON

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ABSTRACT

Purpose. To study rock spallation dynamics in the process of the borehole thermal reaming and analyze energy consumption of the borehole thermal reaming process by plasma jets of the axial plasmatron.

Methods. Field experimental study of rock spallation by plasma jets is carried out with the view to measuring the thermal power of plasma, weight of rock spalls and duration of plasma jets impact on the borehole. VT-200 scales were used to measure the rock spalls weight. In the experimental study, plasma jets flow out directly into the borehole in the granite block. The borehole and plasmatron nozzle parameters are geometrically similar.

Findings. Experimental data are processed in the form of a table that shows the following parameters of individual experiments: duration of the borehole surface treatment by a plasma jet; thermal power of a plasma jet; heat release of a plasma jet, weight of the rock spalls, energy efficiency of the rock spallation process; productivity of the rock destruction. Experimental data are processed in the form of the dependence of energy consumption of the borehole thermal reaming on the duration of the borehole inner surface thermal treatment. The range of thermophysical and plasmodynamic parameters of the plasma torch that allow to achieve rock spallation is determined.

Originality. The linear relationship between the energy consumption in the process of the borehole thermal reaming by low temperature plasma and the duration of the reaming process is revealed, with energy consumption of the reaming process decreasing dramatically with the increase in the process duration.

Practical implications. Methodology of the experimental research into the borehole thermal reaming by plasma jets rock spallation is developed. The results of the study could be applied to borehole drilling processes.

Keywords: *borehole, rock destruction, thermal reaming, plasma, spallation, axial plasmatron*

1. INTRODUCTION

At present time, solution of problems related to spallation and brittle fracture of materials is most topical. For example, insufficient predictability of brittle fracture issues accounts for limitations in increasing the number of oil, gas and geothermal boreholes during drilling in urban areas (Bazargan, Gudmundsson, Meredith, Browning, & Inskip, 2015). The problem of mathematical modelling of rock thermal spallation process is also rather important (Potter, Potter, & Wideman, 2010; Stacey, Sanyal, Potter, & Wideman, 2011; Wideman, Sazdanoff, Unzelman-Langsdorf, & Potter, 2011).

In modern mining, thermal rock spallation is used for a quarry extraction, formation of chambers and stimulation of oil and gas boreholes (Yao, He, Zhang, & Gao, 2005; Renusch, Rudolphi, & Schütze, 2010; Wu, Osawa, Yokokawa, Kawagishi, & Harada, 2010; Brkic, Kant, Meier, Schuler, & von Roh, 2015). The processes of the thermal spallation are used in other branches of engineering and industry. In particular, it is urgent to focus on developing mathematical models of thermal spallation and determining the term of safe exploitation of thermal barrier coatings that are used for manufacturing of turbine blades, combustion chambers of turbo-engines, pipes of boilers etc. (Kihara, Hatano, Nakiyama, Abe, & Nishida, 2006; Walsh & Lomov, 2013; Meier, May, & von Rohr, 2016). Theoretical and experimental investigation of thermal rock destruction by spallation is instrumental in solving problems in aerospace industry, in particular, in mathematical modeling of ablation processes during supersonic plasma jet interaction with the surface of solid bodies (Dmitriev, Goncharov, & Zilbershmidt, 2011).

The relevance of applying thermal destruction methods is based on the wide range of means for realization of rock heating or cooling processes. Forms of thermal impact on the rock have the same physical foundation, namely, the change of power connections potential (Zelenskiy, 1969). Strains of thermal rock minerals expansion are proportional to the thermal expansion coefficient of minerals, Young's modulus and heating temperature. Since Young's modulus and thermal expansion coefficient of rock minerals take different values, rock heating is associated not only with appearance of strains resulting from the emergence of temperature gradient, but also of the structural thermal strains that reach maximal values on the boundaries of mineral grains. Therefore, most of thermal rock destruction products break off the rock mass along the boundaries of mineral grains (Alymov et al., 1969).

When thermal methods of rock destruction are applied, the destruction products break off the rock mass under the influence of shear and tensile thermal stresses. It is known that the strength limit for shearing and stretching is approximately 7 – 10 times less than the strength limit for compression. Hence the thermal method of rock destruction is the most energy saving (Dmitriev & Goncharov, 1990). Temperature increase in the area of heating results in the decrease of strength and aggregate hardness (Falshtynskyi, Lozynskyi, Saik, Dychkovskyi, & Tabachenko, 2016) as well as reduction of rock brittleness which allows to use the thermal methods of rock destruction effectively in the processes of drilling and borehole reaming (Dmitriev & Goncharov, 1990). Thermal methods of reaming, in particular with application of gas jets and arc electrical discharge for rock heating, are most effective.

Plasma burners have the following advantages:

– wider range of adjusting thermal parameters and concentration of the jet power (Dolgopolov et al., 1969);

– reduction of hazardous gases emission (Epshtein, 1969);

– simplified system of automation and distance control of thermal tool compactness (Epshtein, 1969);

– crack propagation in the rock to significant depths in the process of rock thermal destruction (Dolgopolov et al., 1969);

– higher values of the heat transfer coefficient and specific heat flux from the heat-transfer medium to the borehole surface (Koshelev, Tomasov, & Samoylov, 1984).

It should be noted that efficiency of thermal brittle rock destruction increases due to rock strength augmentation, while expenditures for this process realization tend to diminish. The highest efficiency of rock destruction by the thermal method is achieved when the borehole reaming process occurs in well-drillable rocks of sufficiently monolithic mass.

A common feature of the known technical decisions related to the application of the thermal tools with arc electrical discharge for rock destruction is jets of low temperature plasma that flow out of one or several nozzles parallel or at an angle to the borehole axis.

2. REVIEW OF PREVIOUS CONDUCTED EXPERIMENTAL STUDIES

Most known experimental research is focused on determination of rate and temperature values corresponding to the start of rock destruction. In particular, paper (Moskalyev, Pigida, Alymov, Ignatovich, & Bura, 1969) describes plasma burner used for cutting slots in the rock. The burner has the following thermophysical parameters of the torch: efficiency temperature 4000 – 7000°C; maximum specific heat flux – $1.2 \cdot 10^7$ W/m^2; heat transfer coefficient – up to 14 MW/(m$^2 \cdot$K).

The plasma burner application in the process of the thermal drilling resulted in the formation of cracks up to 0.1 mm long which propagated to considerable distance (1 – 2 cm and further) from the drilling channel.

Authors (Zholnach, Dydzinskiy, & Slipchenko, 1972) present 25 – 30 kW plasmatrons used for heating the borehole surface. The distance from the nozzle to the borehole surface was 20 mm, the heat flux of the plasma jet was 5.82 – 11.64 MW/m^2, temperature of the plasma jet was 4000 K.

Paper (Lebedev & Alymov, 1972) deals with the experimental study of the reaming process by 30 – 65 kW plasmatron applied to the boreholes with initial diameter up to 60 mm. Air consumption was 0.005 – 0.010 kg/s and mass-averaged temperature of the plasma flow was within the range of 3000 – 4000 K. When the air pressure was at the level of 0.35 MPa, plasma outflow was occurring in the supersonic mode. The heat flux density on the rock surface was $(1.4 - 2.6) \cdot 10^4$ kW/m^2. The rate of the reaming device movement inside the borehole was in the range of 3 – 8 m/h.

With the view to reducing the concentration of nitrogen oxides in the gases released from plasma jet and increasing the efficiency of energy transfer to the rock, it is suggested to apply an open electric arc (Alymov, Lebedev, & Trofimov, 1976). This will allow to raise temperature on the arc axis to 5000 – 10000 K. Infrared radiation constitutes approximately 50% of the arc radiation spectrum. In the process of experimental investigation, the arc electric current changed from 90 to 150 A, air consumption was within the range of 1 – 3 m^3/h, specific heat flux was 1 MW/m^2.

Application of combustion chamber for increasing thermal efficiency of plasma jets and reducing nitrogen oxides content in a jet is described in (Kasyanov, Musolin, & Snegov, 1976). Parameters of the plasmatron for making chambers in boreholes are shown in Table 1. The results of the experimental research into plasma thermal reaming of boreholes with initial diameters from 100 to 500 mm at depths reaching 70 m are presented in (Kholyavchenko & Osenniy, 1995).

Table 1. Operational characteristics of the plasmatron

Parameter	Value
Thermal power, kW	1200 – 1600
Electrical power, kW	300 – 600
Air consumption, kg/s	0.3 – 0.4
Mass-averaged jet temperature, K	2500 – 2900
Mass-averaged velocity of jet outflow, m/s	1000 – 1500
Thermal efficiency	0.7 – 0.8

The operating characteristics of this plasmatron are shown in Table 2.

Table 2. Operational characteristics of the plasmatron

Parameter	Value
Power, kW	140 – 180
Compressed air pressure, MPa	0.4 – 0.5
Air consumption, m^3/s	0.04 – 0.06
Water pressure for cooling electrodes, MPa	0.8 – 1.0
Water consumption, m^3/s	0.65

Technical indicators of the borehole thermal reaming in the case of magnetite quartzites are shown in Table 3.

Table 3. Technical indicators of thermal reaming

Borehole diameter after thermal reaming, mm	Duration of the thermal reaming process, h	Productivity of the thermal reaming process, m/h	Plasmatron power, kW	Specific air consumption, m^3/min
350	53	0.85	132	1.6
330	47	0.96	130	1.6
350	47	0.96	130	1.6
340	43	1.04	132	1.6
330	41	1.09	129	1.6

Results of the known experimental study (Osenniy, 1997) of the borehole thermal reaming by plasmatron are presented in Table 4.

Table 4. Results of the experimental study

Parameter	Value		
	Quartzites	Magnetite-amphiboles	Magnetite-amphibole-silicates
Plasmatron power, kW	170 – 175	150 – 160	150
Initial borehole diameter, mm	105		
Borehole diameter after reaming, mm	450 – 500	270 – 320	230 – 250
Velocity of the plasmatron nozzle movement in a borehole, m/h	1.0	1.0	0.7
Initial temperature of the heat transfer medium, ºC	No data	No data	950 – 1000
Initial specific heat flux from the heat transfer medium to the rock surface, W/m^2	No data	No data	(8.4 – 9.5)·10^5

It is known that several Ukrainian scientists conducted experimental and theoretical research into the problem of crystal structures destruction by plasma (Zhukov & Sorokopud, 2001; Kleshchov & Terentiev, 2014; Terentiev, Kleshchov, & Gontar, 2015). In particular, as the rock strength rises (over 16 by the Protodiakonov scale of hardness) and its abrasibility increases, technical and economic indicators of conventional mechanic methods of drilling sharply deteriorate, durability of roller bits decreases by 3 – 4 times, while the drilling cost doubles and even triples (Zhukov & Sorokopud, 2001). The highest technical and economic indicators are associated with drilling strong rocks by a combined method implying flame drilling for borehole reaming. The possibility of forming chambers in strong rocks is the main advantage of the thermal method, which allows to reduce drilling costs calculated per 1 m^3 of rock and improve technical and economic indicators of the process.

According to the experimental study (Zhukov & Sorokopud, 2001), in the case when fuel combustion products flow parallel to the borehole wall, heat transfer coefficient is within the range $10^2 – 10^3$ W/(m^2·K), the time of spalls detachment is 1 – 100 s, their thickness being 0.5 – 0.7 mm. In the study of the thermal destruction mechanism during borehole reaming, it was established that thermal micro cracks appear when the temperature of the fine-grained hard rocks heating reaches 700 – 800ºC, while for the large-grained hard rocks the heating temperature should be 500 – 600ºC.

Micro cracks ruin the layer heated up to the temperature of destruction. If the thickness of the heated layer becomes larger than the grain size, spalls tend to detach. Thus, disseminated rocks disintegrate at the temperatures 700 – 900ºC into thin spalls (1 – 2 μm) during rapid heating (1 – 2 s). Coarsely disseminated rocks disintegrate at lower temperature into thicker spalls and it takes more time.

Technical and economic indicators of hard iron rock (f = 16 – 20) drilling technologies are compared in Table 5 (Zhukov & Sorokopud, 2001). Technical and economic indicators of testing the borehole thermal reaming by supersonic flame jet are shown in Table 6.

Table 5. Comparison of technical and economic indicators of hard iron rock drilling technologies

Drilling type	Overall power, kW	Borehole diameter, mm	Specific power, kW·h/dm^3	Volumetric productivity, dm^3/h
Roller-bit drilling	386	250	1.57	245.4
Flame drilling (oxygen)	700	180 – 220	1.5 – 3.4	204 – 456
Flame reaming (air)	1000	400 – 500	0.7	1256 – 1964
Flame drilling (air)	1000	200	5 – 6	200 – 220

Table 6. Technical and economic indicators of testing the borehole thermal reaming by supersonic flame jet

Parameter		Units	TBV-1000	TBV-1500
Initial borehole diameter		mm	250	220
Diameter of the reamed borehole		mm	320 – 440	360 – 500
Borehole depth		m	19	19
Consumption	kerosene	m^3/h	1920	2458
	water	kg/h	100	130
Jet temperature		ºC	1100	1450
Average reaming performance		dm^3/h	500	900

Analysis of scientific literature has testified that thermoelectric tools with arc electrical discharge, i.e. plasmatrons, have a number of advantages compared to conventional devices for rock thermal destruction. Rock destruction by a low-temperature plasma jet is characterized by: cracks propagation to a considerable depth, high values of the heat transfer coefficient and specific heat flux, and the compactness of the thermal tool. One of the main requirements for the process of rock spallation by low-temperature plasma is determination of thermophysical and plasmodynamic parameters of the plasma torch that correspond exceptionally to rock spallation process, while this process does not develop into the rock melting.

3. METHODS

The experimental research aimed at investigating the borehole thermal reaming by an axial plasmatron and energy efficiency of the rock spallation process. The experimental unit for studying the thermal reaming of the borehole within the granite block by the axial plasmatron is shown in Figure 1.

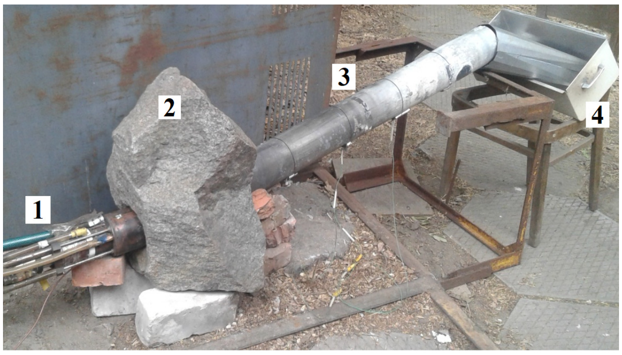

Figure 1. Experimental unit for the thermal reaming of the borehole within the granite block by the axial plasmatron: 1 – plasmatron; 2 – granite block; 3 – pipe for rock spalls transportation; 4 – box for spalls collection

Plasma jet power, its temperature and outflow velocity were determined in the following way:

1. Power consumed by the plasmatron from the electric mains:

$$P_1 = I \cdot U \text{, kW,} \tag{1}$$

where:

I – electric current;

U – voltage.

2. Power taken away of the plasmatron by cooling water:

$$\begin{aligned} P_2 = m_1 \cdot C_p \left(t_0 - t_1\right) + \\ + m_2 \cdot C_p \left(t_0 - t_2\right) + m_3 \cdot C_p \left(t_0 - t_3\right) \end{aligned} \text{, kW,} \tag{2}$$

where:

m_1, m_2, m_3 – mass flow rate of the cooling water running through the cathode, interelectrode insertion and the anode respectively;

t_0, t_1, t_2, t_3 – initial water temperature, temperature of the water at the cathode outlet, water temperature at the interelectrode insertion outlet and temperature of the water at the anode outlet respectively.

3. Thermal power of a plasma jet:

$$Q = P_1 - P_2 \text{, kW.} \tag{3}$$

4. Enthalpy of a plasma jet:

$$H = H_0 + \frac{Q}{G} \text{, kJ/kg,} \tag{4}$$

where:

$H_0 = 303.3$ kJ/kg;

G – mass flow rate of the plasma forming gas, kg/s.

5. Mass averaged plasma jet could be determined by the graphical relationship between air enthalpy and its temperature.

6. Specific air plasma density could be determined by its temperature.

7. Plasma jet outflow velocity could be calculated by:

$$V = \frac{G}{\rho \cdot S} \text{, m/s,} \tag{5}$$

where:

ρ – specific plasma density, kg/m^3;

S – cross-section area of the plasmatron nozzle, m^2.

Figure 2 shows the process of the borehole thermal reaming by the plasma jet of the axial plasmatron. In the experimental study, the following parameters were monitored: I, U, m_1, m_2, m_3, t_0, t_1, t_2, t_3, G; because they are necessary for calculating the power of a plasma jet, its temperature and outflow velocity.

Figure 2. The process of the borehole thermal reaming by the plasma jet of the axial plasmatron

The plasmatron nozzle outlet *1* was joined with the borehole inlet in the granite block *2*. After the granite spal-lation (Fig. 3), the spalls got into the pipe *3* through which they were transported into the box *4* by the plasma flow.

After switching off the plasmatron, air was blown through the tin pipe. As the experiment was over, the spalls were weighed (Fig. 4) on VT-200 scales which ensure accuracy class 4 and the accuracy of measurement ±10 mg. Initial temperature of the granite block was within 18 – 20ºC. Initial diameter of the borehole was 105 mm. Borehole depth was 300 mm.

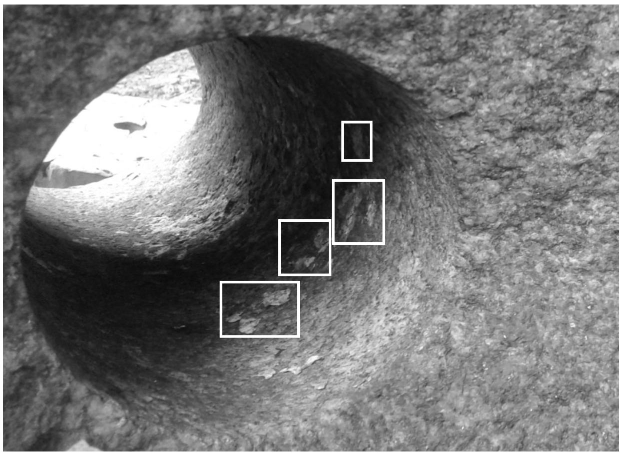

Figure 3. Spallation marks in the borehole of the granite block

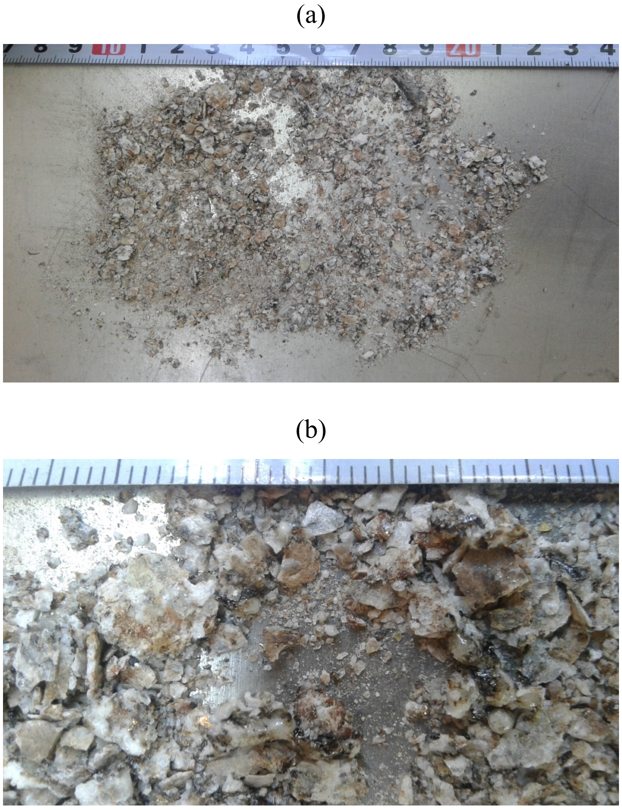

Figure 4. Rock spalls after the borehole thermal reaming by the axial plasmatron: (a) small scale; (b) large scale

The aim of the experimental study was to determine the weight of the spalls in order to calculate the energy efficiency of the spallation process. The values of parameters for the experimental study of the borehole thermal reaming by the axial plasmatron are given in Table 7 and 8.

Table 7. Parameters of the axial plasmatron

Parameter	Value
Air consumption G_{air}, kg/s	0.006
Inner diameter of the plasmotron nozzle d_{in}, m	0.034
Length of the plasmotron nozzle l_n, m	0.09
Thickness of the pipe neck wall δ, m	0.003
Length of the pipe neck l_{pn}, m	0.098

The geometrical parameters of the borehole and the plasmatron nozzle are assumed to be geometrically similar to technological and design parameters of the plasmatron and borehole diameter before the beginning of the thermal reaming process.

4. RESULTS AND DISCUSSION

Figure 4 shows that the particles up to 5 mm are predominant among the spalls. The plasmatron provided such a range of thermophysical and plasmodynamic parameters of a plasma torch at which the rock melting mode was not observed (Fig. 4). Figure 5 shows energy efficiency of the borehole thermal reaming process of our experimental study in comparison with the other research (Zhukov & Sorokopud, 2001).

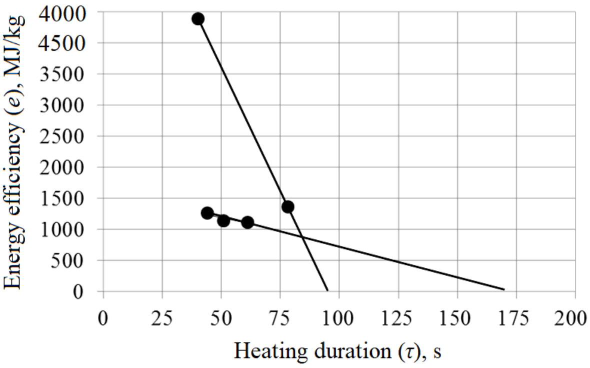

Figure 5. Influence of the borehole inner surface heating duration on the energy efficiency of the borehole thermal reaming

Analysis of Figure 5 allows to make the following conclusions:

1. There is almost no spallation, if duration of the thermal reaming process does not exceed 90 s, which agrees with the data from (Zhukov & Sorokopud, 2001); in this case energy efficiency of the thermal reaming process is more than 1000 MJ/kg.

2. Increase in the plasmatron operation time, i.e. duration of the thermal reaming process, leads to the sharp decrease in the energy efficiency of the process. As stated by the authors in (Zhukov & Sorokopud, 2001), achieving thermal efficiency range of 0.97 – 4.48 MJ/kg is possible when the process duration exceeds 90 s, lasting up to 170 s, the plasmatron thermal power keeping within the range 53.2 – 57.3 kW. This is quite comparable with the experimental study (Zhukov & Sorokopud, 2001), where the plasmatron thermal power of 100 kW corresponds to energy efficiency of the thermal reaming process 0.97 – 4.48 MJ/kg while the process duration is 100 s.

Future experimental studies of the borehole reaming by a low-temperature plasma jet will be related to application of the plasma jets flowing out of the nozzle at an angle to the borehole axis which will allow to increase the intensity of interaction between the plasma jet and the borehole surface due to longer duration of the plasma jets movement along the borehole surface. In turn, it will lead to the energy intensity reduction of the borehole thermal reaming process by a low-temperature plasma.

Table 8. Parameters of the experimental research into the borehole thermal reaming by the axial plasmatron

Parameters	No. of the experiment					
	1	2	3	4	5	Averaged values
Operating time of the plasmatron τ, s	40	51	44	61	78	54.8
Plasma thermal power Q, kW	54.8	57.3	54.9	55.6	53.2	55.2
Plasma heating value in the experiment, kJ	2193.3	2416.6	2912.4	3375.8	4125.9	3004.8
Spalls weight m, kg	0.0005	0.0021	0.0023	0.0030	0.0030	0.00218
Energy efficiency of the spallation process, kJ/g	4386.6	1150.7	1266.3	1125.2	1375.3	1860.8

5. CONCLUSIONS

The present research resulted in determination of thermophysical and plasmodynamic parameters of the plasma torch exceptionally related to rock spallation process without transition into the rock melting mode. The study allowed to define the time range necessary to achieve spallation energy efficiency of 0.97 – 4.48 MJ/kg for rock hardness coefficient $f = 8 – 12$ and plasma thermal power 53.2 – 57.3 kW.

The relationship between energy consumption in the process of the borehole thermal reaming by low temperature plasma and the duration of the reaming process is almost linear, the energy consumption of the reaming process decreasing dramatically with the increase in the process duration.

It should be noted that the efficiency of the plasma thermal energy use was not investigated in the present experimental study for the following reasons:

– the depth of the borehole was less than the length of the low-temperature plasma torch;

– as seen from Figure 3, the plasma torch flowing out of the plasmatron nozzle has a certain expansion angle, thus, interaction between the torch and the inner surface of the borehole starts at a certain distance from the inlet orifice of the borehole.

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ЕКСПЕРИМЕНТАЛЬНЕ ДОСЛІДЖЕННЯ ПРОЦЕСУ ТЕРМІЧНОГО РОЗШИРЕННЯ СВЕРДЛОВИНИ ОСЬОВИМ ПЛАЗМОТРОНОМ

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Мета. Дослідження динаміки лущення гірської породи в процесі термічного розширення свердловини та енергоємності процесу термічного розширення свердловини плазмовим струменем осьового плазмотрона.

Методика. В роботі виконано натурне експериментальне дослідження лущення гірської породи струминою плазми. Сутність експерименту полягала у вимірюванні теплової потужності плазми, маси сколених частинок гірської породи та тривалості впливу плазмового струменя на свердловину. Для вимірювання маси сколених частинок гірської породи використовувались ваги ВТ-200. В експериментальному дослідженні струмина плазми витікає безпосередньо в свердловину в блоці міцного граніту. Дотримано геометричну подобу параметрів свердловини та сопла плазмотрона.

Результати. Виконано обробку дослідних даних у вигляді таблиці, в якій наведено наступні параметри окремих дослідів: тривалість впливу плазмового струменя на свердловину; теплова потужність плазмового струменя; теплота плазмового струменя, маса сколених частинок породи, енергоємність процесу лущення гірської породи; продуктивність руйнування гірської породи. Виконано обробку дослідних даних у вигляді залежності енергоємності процесу термічного розширення свердловини від тривалості термічної обробки внутрішньої поверхні свердловини.

Наукова новизна. Виявлено лінійну залежність енергоємності процесу термічного розширення свердловин низькотемпературною плазмою від тривалості процесу розширення, при цьому енергоємність процесу розширення стрімко зменшується зі збільшенням тривалості процесу.

Практична значимість. Розроблено методику експериментального дослідження термічного розширення свердловини шляхом лущенням гірської породи струминою плазми. Отримані результати впливу високотемпературних струмин плазми в процесах крихкого руйнування гірських порід можуть бути застосованими в процесах буріння свердловин.

Ключові слова: *свердловина, руйнування гірських порід, термічне розширення, плазма, лущення, осьовий плазмотрон*

ЭКСПЕРИМЕНТАЛЬНОЕ ИССЛЕДОВАНИЕ ПРОЦЕССА ТЕРМИЧЕСКОГО РАСШИРЕНИЯ СКВАЖИНЫ ОСЕВЫМ ПЛАЗМОТРОНОМ

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Цель. Исследование динамики шелушения горной породы в процессе термического расширения скважины и энергоемкости процесса термического расширения скважины плазменной струей осевого плазмотрона.

Методика. В работе выполнено натурное экспериментальное исследование шелушения горной породы струей плазмы. Сущность эксперимента заключалась в измерении тепловой мощности плазмы, массы сколотых частиц горной породы и длительности воздействия плазменной струи на скважину. Для измерения массы сколотых частиц горной породы использовались весы ВТ-200. В экспериментальном исследовании струя плазмы следует непосредственно в скважину в блоке крепкого гранита. Соблюдено геометрическое подобие параметров скважины и сопла плазмотрона.

Результаты. Опытные данные представлены в виде таблицы, в которой сведены следующие параметры отдельных опытов: продолжительность воздействия плазменной струи на скважину; тепловая мощность плазменной струи; теплота плазменной струи, масса сколотых частиц породы, энергоемкость процесса шелушения горной породы; производительность разрушения горной породы. Опытные данные обработаны в виде зависимости энергоемкости процесса термического расширения скважины от продолжительности термической обработки внутренней поверхности скважины. Определен диапазон теплофизических и плазмодинамичних параметров плазменного факела при которых достигается процесс шелушения породы.

Научная новизна. Выявлена линейная зависимость энергоемкости процесса термического расширения скважин низкотемпературной плазмой от продолжительности процесса расширения, при этом энергоемкость процесса расширения стремительно уменьшается с увеличением продолжительности процесса.

Практическая значимость. Разработана методика экспериментального исследования термического расширения скважины путем шелушения горной породы струей плазмы. Полученные результаты воздействия высокотемпературных струй плазмы в процессах хрупкого разрушения горных пород могут быть применены в процессах бурения скважин.

Ключевые слова: *скважина, разрушение горных пород, термическое расширение, плазма, шелушение, осевой плазмотрон*

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