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A. Yu. Dreus[1], Cand. Sc. (Tech.), Assoc. Prof.,
A. K. Sudakov[2], Dr. Sc. (Tech.), Assoc. Prof.,
A. A. Kozhevnikov[2], Dr. Sc. (Tech.), Prof.,
Yu. N. Vakhalin[3], Cand. Sc. (Tech.), Assoc. Prof.

1 – Oles Honchar Dnipropetrovsk National University, Dnipropetrovsk, Ukraine, e-mail: dreus.a@dnu.dp.ua
2 – State Higher Educational Institution "National Mining University", Dnipropetrovsk, Ukraine, e-mail: sydakovy@ukr.net
3 – State Higher Educational Institution "Ukranian State University of Chemical Technologies", Dnipropetrovsk, Ukraine

STUDY ON THERMAL STRENGTH REDUCTION OF ROCK FORMATION IN THE DIAMOND CORE DRILLING PROCESS USING PULSE FLUSHING MODE

А. Ю. Дреус[1], канд. техн. наук, доц.,
А. К. Судаков[2], д-р техн. наук, доц.,
А. О. Кожевников[2], д-р техн. наук, проф.,
Ю. М. Вахалін[3], канд. техн. наук, доц.

1 – Дніпропетровський національний університет ім. О. Гончара, м. Дніпропетровськ, Україна, e-mail: dreus.a@dnu.dp.ua
2 – Державний вищий навчальний заклад „Національний гірничий університет", м. Дніпропетровськ, Україна, e-mail: sydakovy@ukr.net
3 – Державний вищий навчальний заклад „Український державний хіміко-технологічний університет", м. Дніпропетровськ, Україна

ДОСЛІДЖЕННЯ ТЕРМІЧНОГО ЗНИЖЕННЯ МІЦНОСТІ ГІРСЬКОЇ ПОРОДИ ПРИ АЛМАЗНОМУ БУРІННІ З ІМПУЛЬСНОЮ ПРОМИВКОЮ

Purpose. The study of pulse flushing impact on weakening of rock formation in the course of diamond core drilling using diamond bits.

Methodology. Theoretical research of rock formation softening processes under transient thermal impact is based on the theory of thermoelasticity. Comparative analysis of thermal stress condition of rock formation in the course of diamond core drilling using both the pulse and continuous flushing modes was carried out in the course of the research.

Findings. The process of rock formation breaking in the course of diamond core drilling using stationary and transient (pulse) flushing with drilling fluid was studied herein. Conditions for transition of rock formation fractures to movable state and strength reduction have been defined. The estimated relation between the fracture development rate and delay of rock formation decomposition are obtained herein. The study revealed that under the pulse mode of drilling fluid supply conditions appear for thermal decomposition of rock formation. Owing to a greater, as compared to the continuous flushing mode, amplitude of temperatures in the borehole working area, strength reduction of the rock formation surface occurs. When boring granitic rocks, its strength reduction is 12 % on average.

Originality. The analysis of thermal stress condition of the rock formation was carried out for the first time along with grounding of the possibility to employ the thermal cycle effect to enhance the efficiency of rock decomposition in the course of the core drilling using diamond bits. For the first time ever the characteristics of thermal decomposition of rock formation were determined as follows: minimum dimensions of fractures and minimum delay time of decomposition commencing; the evaluation of rock formation strength reduction for the diamond core drilling process. The study revealed that the technique of pulse supply of the drilling fluid stipulates for notable reduction of energy consumption of the rock formation decomposition process.

Practical value. The outcomes of the study can be applied to develop pulse techniques of wells boring, as well as to establish efficient and cost saving parameters of the process.

Keywords: *diamond core drilling, pulse flushing, thermal stresses*

Introduction. Boreholes pulse flushing [1–3] has been attracting increased attention of drilling method designers. The outcomes of experimental research reveal notable enhancing of the number of performance indices of boreholes core drilling using the pulse flushing method; in particular, they include more efficient washing-over of borehole bottoms, 30–40 % reduced pumping equipment power consumption as compared to the continuous flushing method, elimination of reservoir horizon incrusting etc. The essential result of using the pulse flushing technique is in speeding up the mechanical velocity of borehole drilling. As of today, however, there has been no scientific theoretical grounding of the achieved effect. Among the probable mechanisms ensuring the enhanced rate of rock decomposition might be the process of thermal fatigue reduction of the rock formation under alternating high and low temperatures. In the majority of cases, rock formations have a web of micro-fractures which are allocated throughout the rock with certain density [4]. To those are added the fractures in rock formation caused by application of rock decomposition tools (the fracture process zone). Thermal gradients in borehole bottoms might range within 600 °C and up. This results in significant cyclic thermal stress in the rock formation. Thermal cycling caused by drilling tools results in developing of fatigue in rock formation, growth of the existing fractures and more efficient decomposition of the rock.

Therefore, the research of thermal mechanical processes in the course of core drilling using the pulse flushing method can be of interest from the point of view of searching for reserves of enhancing the performance, and cutting energy consumption of rock formation decomposition works.

Analysis of the recent research and unsolved aspects of the problem. A diamond core bit consists of a steel body and matrix divided by washing-over channels into segments. Due to the heat induced by friction between the bit and the rock in the course of rock formation drilling, the surface of borehole working face is heated within the temperature range of 300–800 °C depending on the flushing mode. Following the heating segment, there is a washing-over segment located above the same drilling zone. Drilling fluid at a temperature within 20–40 °C is flowing along the washing-over segment. Owing to the drilling bit rotating, therefore, the surface of rock formation is under thermal cycling impact. Switching from the heating to shock cooling modes results in alteration of thermal stress condition of the rock formation, e.g. from its extension to contraction. Since rock formation resistance to extension is a magnitude order lower than that of contraction, the thermal gradient, therefore, contributes to its strength reduction. The outcomes of the experimental research [5] reveal that thermal cycling of rock formation, even in the absence of external loads, results in accumulation of defects in polycrystal material thus providing further efficient decomposition of the rock formation.

The processes of rock formation decomposition under combined mechanical and thermal impacts were the subject of the research in articles [6, 7], while those under thermal cycling impacts were dealt with in articles [8, 9]. The methodology, approach and models developed in the mentioned above articles can be used for studying thermal cycling effects in the core drilling process using diamond bits.

Analysis of outcomes of the research of thermal and thermal-cycling decomposition of rock formation demonstrates that strength reduction of rock formation is defined by two interrelated criteria: thermal gradient between the heated rock formation and cooling environment, and decomposition delay time. The time of delay is the interval after beginning of cooling required to initiate the fracture development process.

In the core drilling process while using diamond bits, the time of contact between the borehole working face and cooling fluid makes a few centiseconds. With the regular modes of washing-over, the thermal gradient in the borehole working face is about 300 °C which is not enough to implement the thermal cycling effect efficiently. The pulse mode of flushing, on the other hand, stipulates for ensuring arbitrary large thermal gradients; however, the limiting factor here is thermal resistance of the drilling tools. The matter of choosing the proper pulse washing-over modes to ensure operating performance of the drilling tools is dealt with in article [10], which demonstrates possibility of ensuring the flushing process with thermal gradients up to 600 °C.

Various methods are applicable to provide targeted utilization of thermal processes in rock formation in order to enhance the efficiency of its decomposition processes. One of the approaches suggested here is to vary the geometry of rock formation decomposition tools by changing the length of operating sectors and drilling fluid courses. Therefore, the certain amendments to the design of the drilling bit must be implemented. The capabilities of this method are limited by the finite dimensions of the drilling tools. On the other hand, changing of the drilling bits design causes the need to adjust the following drilling modes parameters: the axial load and drilling bit rotating frequency, which, in turn, results in changing the temperature mode of the drilling process.

The alternative approach stipulates for providing the borehole working face of non-reversing processes of rock formation cracking by controlling the input of the drilling fluid, which is exactly the case for the pulse flushing mode. This method can be implemented by controlling the thermal condition of the borehole working face using the mode parameters, in particular, using the pulse supply of drilling fluid.

Objective of the study is to research the impact of drilling fluid pulse supply on rock formation strength reduction.

Presentation of the main research. We shall analyze the impact of thermal modes in the borehole working face under the continuous and pulse flushing onto the conditions of fracture development in rock formation. It is hereby assumed that among the fractures in the fracture process zone there are always some fractures reaching the surface of the borehole bottom. Due to the temperature drop from T_h to T_c the following expansion tensions emerge in the parallel surfaces of the borehole bottom

$$\sigma_* = -\frac{E\beta\left(T_h - T_c\right)}{1-\mu},$$

where E is Young's modulus (modulus of elasticity) of the rock formation; β is linear expansion coefficient of the rock formation; is Poisson's ratio. The minimum length of the fraction l_* developed by the tension can be defined by Griffith's energy fraction criterion

$$\sigma_* = \frac{K\sqrt{2}}{\pi\sqrt{l_*}}, \qquad (1)$$

where K is rock formation cohesion modulus. The condition for transition of fractures to nonstationary state is defined by the following inequation

$$\pi N_0 < K,$$

where N_0 is stress intensity ratio. According to the theory of equilibrium cracks [9], this ration will be equal to

$$\pi N_0 < \frac{\sqrt{2l}}{\pi}\int_0^l \frac{P(x)}{\sqrt{l^2 - x^2}}dx, \qquad (2)$$

where $P(x)$ is the function of normal stress in solid body in the fracture; l is the length of the fracture. For the thermal stresses under intense cooling of the borehole working face this function will be defined as

$$P(x) = \sigma_* \cdot \mathrm{erfc}\left(\frac{x}{2\sqrt{a\tau}}\right),$$

where a is thermal conductivity ratio, τ is time. Gaussian error function can be presented as expansion in a series

$$\mathrm{erfc}\left(\frac{\mathrm{x}}{2\sqrt{\mathrm{at}}}\right) = \\ = 1 - \frac{x}{\sqrt{\pi a\tau}}\left(1 - \frac{1}{3}\left(\frac{x}{2\sqrt{a\tau}}\right)^2 + \frac{1}{10}\left(\frac{x}{2\sqrt{a\tau}}\right)^4 - \ldots\right). \qquad (3)$$

For approximate calculation we can take the first two additive components in the above series (3). After substitution of (3) into (2) taking into account (1), we obtain the following

$$\sqrt{\frac{l_*}{l}} < \frac{2}{\pi}\left[\int_0^l \frac{1}{\sqrt{l^2 - x^2}}dx - \frac{1}{\sqrt{\pi a\tau}}\int_0^l \frac{x}{\sqrt{l^2 - x^2}}dx\right]. \qquad (4)$$

Having calculated the integrals in the formula above (4), we obtain the following inequation below

$$\sqrt{\frac{l_*}{l}} < \frac{2}{\pi}\left[\frac{\pi}{2} - \frac{l}{\sqrt{\pi a\tau}}\right]. \qquad (5)$$

Expression (5) determines the relation between the necessary cooling time and initial fracture length. After transformations, this expression can be presented as equation in the following non-dimensional form

$$\mathrm{Fo} = \frac{4}{\pi^3}\frac{L^3}{\left(\sqrt{L} - 1\right)^2}, \qquad (6)$$

where $\mathrm{Fo} = \frac{a \cdot \tau}{l_*^2}$ is Fourier criterion (non-dimensional time); $L = \frac{l}{l_*}$ is non-dimensional length of the fracture. From the above equation (6) the formula below for non-dimensional rate of the fracture development can be easily obtained

$$V = \frac{\mathrm{d}L}{\mathrm{d\,Fo}} = \frac{\pi^3}{4L}\frac{(\sqrt{L} - 1)^3}{\left(2\sqrt{L} - 3\right)}. \qquad (7)$$

Dependence of cooling time (6) and development rate (7) on the fracture length is shown in Fig. 1 and Fig. 2 below.

Based on the length l_*, it is evident that fractures with their lengths $l < l_*$, or $L < 1$, will not develop. When $L > 1$ as shown in Fig. 1 above, there are two possible options. If under the applied heat $1 < L < L_{\min}$, then cooling time is lower than minimum time, therefore the rock formation will elongate without any visible cracking. The existing fractures will not transfer to the non-stationary mode, as it is specified by negative values of fracture development rate in Fig. 2 above. However, the layer will build up where elongating tensile stresses are equal to the effect of concentrated force, and the fracture is getting closer to its dynamic-equilibrium state. When $\mathrm{Fo}_{\min} = \mathrm{Fo}_{\min}$, the fracture starts its dynamic development and grows steadily. The fracture development rate will be at its maximum for the fracture which has just started its dynamic development, and it will abate in the course of develop-

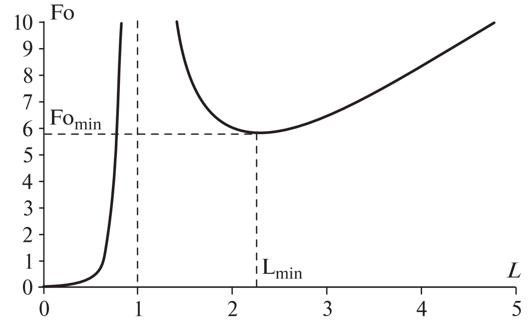

Fig. 1. Dependence of non-dimensional time Fo on fracture length L

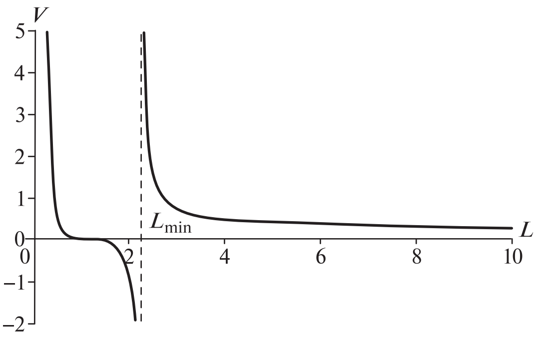

Fig. 2. Dependence of non-dimensional rate V on the fracture length L

ment. Function Fo(L) will reach its minimum at $L_{\min} = 2.25$, while non-dimensional time $\mathrm{Fo}_{\min} \approx 5.87$. The time corresponding to the minimum point of the function shall be considered the time of delay of decomposition beginning process.

The results of estimating the thermal stressed condition of rock formation under continuous and pulse modes of flushing are shown below. The demonstrated rock formation is granite, where $a = 8.3 \cdot 10^{-6}$ m^2/sec, $E = 2.9 \cdot 10^{10}$ N/m^2, $\beta = 1 \cdot 10^{-5}$ K^{-1}, $\mu = 0.3$, $K = 5 \cdot 10^6$ N/m$^{3/2}$. The results of the analysis are shown dimensionally in Table below.

Table

Parameters that define the process of rock formation thermal decomposition under various modes of flushing

Flushing mode	Continues	Pulse
Thermal gradient , K	300	600
Tension σ_* N/m^2	$-9.667 \cdot 10^7$	$-1.933 \cdot 10^8$
Minimum length of fracture l_*, opened by σ_*, mm	0.542	0.136
Minimum length of fracture required for steady development, $l_{\min}$, mm	1.220	0.305
Time of delay $\tau_{\min}$, sec	0.208	0.013

As Table above shows, during the pulse mode of flushing the minimum length of the fracture, which is opened by the corresponding tension of elongation, is 4 times as low as the length of the fracture during the continuous flushing mode. Temperature gradient allows creating higher thermal tensions in rock under impulse mode. Therefore, during the pulse mode much more micro-fractures will be prone to further development, while their initial dimensions will be much lower. The delay time of the decomposition beginning decreases by an order of magnitude compared to the continuous mode. Given that the time of contact of drilling fluid with the rock formation is about 0.044 sec, it becomes obvious that during the pulse flushing conditions ensured to utilize the thermal cycling effect are significantly more beneficial than in the course of continuous flushing.

Let's consider the matter of strength reduction of the surface of the borehole working face under the thermal cycling impact. It is assumed that there is a fracture with its length l_0 in the surface layer. To ensure decomposition of the solid body with such a fracture, the tensile strength σ_0 required. If, upon the period of time τ, the fracture has developed to its length l, the respective tension of decomposition has dropped to σ. The strength reduction will be defined by the ratio $\gamma = \frac{\sigma}{\sigma_0}$. In article [9] it is shown that

$$\gamma = \frac{\sigma}{\sigma_0} = \sqrt{\frac{l_0}{l}}.$$

Therefore, during the time T the strength of the rock formation will drop to

$$\gamma = \left(\frac{l}{l_0}\right)^{-\frac{1}{2}} = \left(\frac{l_0 + \Delta l}{l_0}\right)^{-\frac{1}{2}} = \left(1 + \frac{1}{l_0}\int_0^T \upsilon(\tau)\,d\tau\right)^{-\frac{1}{2}},$$

where $\upsilon = V \cdot \frac{a}{l_*}$ is the fracture development rate. According to the data of [4], the length of initial (natural) micro-fractures, which play their role in thermal decomposition methods, ranges within 0.048–0.85 mm. The minimum length of fractures opened by thermal elongating tension during diamond core drilling will correspond to the range presented in Table above. The diagram in Fig. 3 below demonstrates the estimation results for strength reduction for fractures with their length ranging from 0.31 to 0.85 mm. It is evident from the diagram that the rock formations containing the fractures with their dimensions close to the minimum value will feature the maximum strength reduction.

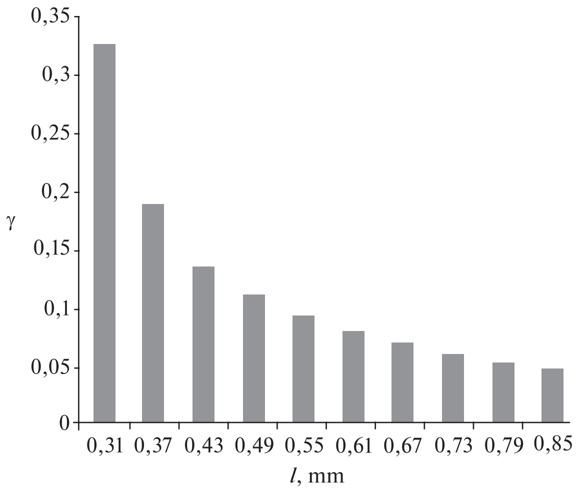

Fig. 3. Association of the rock formation strength retorigression γ with length of fractures l

The length increasing, the fractures become more stable because greater tension is required for their effective opening. Therefore, the value of strength reduction caused by thermal cycling impact is only 6 % for longer fractures, and it grows to 32 % for the fractures which their dimensions closer to the minimum required figures. The average strength reduction estimated for all the analyzed lengths comprises 12%.

Research conclusions and recommendations for further research. The present article dealt with the mechanism of strength reduction of rock formation due to alternating impacts of high and low temperatures in the diamond core drilling process. It was revealed that owing to significant thermal gradients in the course of pulse flushing it is possible to achieve the effects of rock formation strength reduction by 12% on average. The results of the paper are recommended as the basis for choosing energy saving modes of pulse drilling operations.

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Экспериментальные исследования разупрочнения крепких горных пород при нагреве трением фрикционных элементов термомеханической коронки / С. А. Ермаков, Л. Н. Федоров, Д. С. Ващенко, Р. М. Скрябин. // Горный информационно-аналитический бюллетень. – 2010. – № 7. – С. 151–155.

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Мета. Дослідження впливу імпульсної подачі промивальної рідини при бурінні алмазними коронками на зниження міцності гірської породи.

Методика. Теоретичне дослідження процесів зниження міцності гірської породи при нестаціонарному термічному впливі на основі теорії пружності. Виконано порівняльний аналіз термопружного стану породи під час буріння з імпульсним и неперервним режимами промивання.

Результати. Визначені умови переходу тріщин у рухомий стан та зниження міцності породи. Отримані розрахункові співвідношення для швидкості розвитку тріщин і часу затримки процесу руйнування. Показано, що за імпульсного режиму подачі промивальної рідини у гірській породі створюються умови для термічного руйнування. За рахунок більш високої, у порівнянні з режимом неперервної промивки, амплітуди температури на вибої свердловини, відбувається зниження міцності. При бурінні граніту середнє зниження міцності складає 12 %.

Наукова новизна. Уперше виконано аналіз термопружного стану породи та обґрунтовано можливість використання термоциклічного ефекту для підвищення ефективності процесу руйнування гірської породи при бурінні алмазними коронками. Уперше визначені характеристики процесу термічного руйнування породи: мінімальні розміри тріщин і мінімальний час затримки початку руйнування, виконано оцінку зниження міцності породи для алмазного буріння. Показано, що технологія імпульсної подачі промивальної рідини сприяє зниженню енергоємності процесу руйнування породи.

Практична значимість. Результати роботи можуть бути використані під час розробки технологій імпульсного буріння свердловин, для визначення енергоефективних параметрів процесу.

Ключові слова: *алмазне буріння, імпульсне промивання, температурні напруження*

Цель. Исследование влияния импульсной подачи промывочной жидкости при бурении алмазными коронками на разупрочнение горной породы.

Методика. Теоретическое исследование процессов разупрочнения горной породы при нестационарном термическом воздействии на основе теории термоупругости. Выполнен сравнительный анализ термонапряженного состояния породы при бурении с импульсным и постоянным режимами промывки.

Результаты. Определены условия перехода трещин в подвижное состояние и снижение прочности породы. Получены расчетные соотношения для скорости развития трещин и времени задержки процесса разрушения. Показано, что при импульсном режиме подачи промывочной жидкости в горной породе создаются условия для термического разрушения. За счет более высокой, чем для режима с постоянной промывкой, амплитуды температуры на забое скважины происходит разупрочнение поверхностного слоя горной породы. При бурении по граниту среднее снижение прочности составляет 12 %.

Научная новизна. Впервые выполнен анализ термонапряженного состояния породы и обоснована возможность использования термоциклического эффекта для повышения эффективности процесса разрушения горной породы при бурении алмазными коронками. Впервые определены характеристики процесса термического разрушения породы: минимальные размеры трещин и минимальное время задержки начала разрушения, выполнена оценка снижения прочности породы для алмазного бурения. Показано, что технология импульсной подачи промывочной жидкости способствует снижения энергоемкости процесса разрушения породы.

Практическая значимость. Результаты работы могут быть использованы при разработке технологий импульсного бурения скважин, для определения энергоэффективных параметров процесса.

Ключевые слова: *алмазное бурение, импульсная промывка, температурные напряжения*

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Chen Zijian[1],
Yu Baohua[1],
Yuan Junliang[2],
Zhang Yanan[1],
Deng Jingen[1]

1 – State Key Laboratory of Petroleum Resource and Prospecting, China University of Petroleum, Beijing, China
2 – China National Offshore Oil Corporation Research Institute, Beijing, China

DETERMINATION OF FACTURE TOUGHNESS OF ROCKS OF A SHALE GAS RESERVOIR USING STRAIGHT-NOTCHED BRAZILIAN DISC (SNBD) SPECIMEN AND WELL LOGS

Чень Цзицзянь[1],
Юй Баухуа[1],
Юань Іюньлян[2],
Чжан Янань[1],
Ден Джінгень[1]

1 – Державна провідна лабораторія запасів нафти та розвідувальних робіт, Китайський Нафтовий Університет, м. Пекін, Китай
2 – Дослідний Інститут Китайскої національної шельфової нафтової корпорації, м. Пекін, Китай

ВИЗНАЧЕННЯ МІЦНОСТІ НА РОЗРИВ ПОРІД РОДОВИЩА СЛАНЦЕВОГО ГАЗУ З ВИКОРИСТАННЯМ ЗРАЗКА ПРЯМОШОВНОГО БРАЗИЛЬСЬКОГО ДИСКА (SNBD) І КАРОТАЖУ

The straight-notched Brazilian disc (SNBD) specimen is used to test the mode-I and mode-II fracture toughness of a shale gas reservoir. The tests are conducted on 14 shale specimens which are taken from the shale gas reservoir in the southwest Chongqing, China. The technique of high-pressure water jet cutting is applied to process the pre-existing notch within specimens to avoid the influence of central hole on the notch to ensure the accuracy of the testing results. Based on the testing results, mode-I and mode-II fracture toughness prediction models of the shale gas reservoir are established. The predicted fracture toughness and testing results show good agreement. The results indicate that the mode-I and mode-II fracture toughness of the shale gas reservoir are in direct proportion to the rock density and interval transit time, and inversely proportional to the shale content. The prediction models can be used to establish continuous fracture toughness profiles of the shale gas reservoir and effectively guide the selection of optimal layer before hydraulic fracturing.

Key words: *shale gas reservoir, straight-notched Brazilian disc, fracture toughness, well logging*
