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ANALYTICAL STUDY OF HEAT TRANSFER IN ABSORPTIVE HORIZONS OF BOREHOLE AT FORMING CRYOGENIC PROTECTING OF THE PLUGGING MATERIAL

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АНАЛІТИЧНЕ ДОСЛІДЖЕННЯ ПРОЦЕСІВ ТЕПЛОПЕРЕНОСУ В ПОГЛИНАЮЧОМУ ГОРИЗОНТІ БУРОВОЇ СВЕРДЛОВИНИ ПРИ ФОРМУВАННІ КРІОГЕННОГО ЗАХИСТУ ТАМПОНАЖНОГО МАТЕРІАЛУ

Purpose. Development of the method for calculating parameters of rock freezing process in cryogenic screen formation using a new innovative technology of elimination of the drilling liquid absorption in the well.

Methodology. The tasks set were solved using analytical, experimental methods of thermal physics and heat and mass transfer. Theoretical analysis is based on an analytical solution of heat transfer problem in frozen semi-infinite cylindrical layer.

Findings. The paper considers physical and mathematical statement of the problem. A mathematical model of heat transfer processes in rock massive under refrigerant impact was proposed. Temperature field dynamics in rocks is presented and relation of freezing time to frozen layer efficiency is studied. Analytical expressions for calculating the parameters of protective inverted cryogen screen formation in the absorptive horizon of a borehole are obtained.

Originality. For the first time, the relation of the efficiency of the inverted cryogen screen (a frozen layer around rocks around a borehole) to the heat treatment time of the absorptive horizon of a borehole and refrigerant temperature was defined.

Practical value. Innovative cryogenic technology of elimination of washing liquid absorption was developed. An analytical solution of heat transfer in rock at inverted cryogen screen formation around a borehole is obtained. Regularity of rock freezing time relation to inverted cryogenic screen width is established.

Keywords: *well, elimination of absorption, cryogenic technology, heat transfer*

Introduction. The process of borehole drilling is accompanied by a number of geological complications. One of the most common complications is the absorption of washing liquid. The elimination of absorptions takes a large proportion of time and money which is spent on well construction.

Analysis of the recent researches and publications. The reasons which cause the absorption of washing liquids in wells and analysis of methods for dealing with it [1] are discussed in detail.

There are no reliable technologies to eliminate these types of complications at the present time. The effectiveness of current technologies and materials does not exceed 70 %.

Prevention of drilling fluid absorption is much cheaper than its elimination. Technologies of the absorption prevention have been the subject of many works.

Prevention of liquid absorption can be realized by adjusting properties of drilling fluids, and/or by decreasing differential pressure on absorbing horizon [2, 3]. These technologies are limited in practice, and are not very efficiency.

The elimination of the absorption is provided by plugging of the washing channels with solidifying and non-solidifying cement slurry. Thus, a waterproof screen is created around the well.

Currently, a large number of technologies and technical means have been developed to eliminate absorption of drilling fluid using grouting water-based materials with mineral or synthetic additives. These issues have been considered by Bulatov A., Ivacheva L., Kipko, E., Krylov V., Lipatov N., Mysliuk M., Polozov Yu., Rafieko I., Spichak, Y., Titkov I., Tian P., Yakovlev A., Yasov V., and others [1]. However, efficiency of these water-based composites is sufficient.

The most common method of isolation of an absorbing horizon is filling the absorption channels with cement slurries. The cement stone is obtained due to hydration of binder. Such cement slurries can include composites based on cement as well.

However, properties of cement mortar change at contact with borehole fluid (washing liquid, fluid) because it is diluted and sedimentation process takes place. Due to efficiency of isolation of the absorbing horizon its efficiency decreases, and subsequent cementing operations could be required.

Department of the Technology Prospecting Deposit at National Mining University (Dnipro city, Ukraine) gained considerable experience in dealing with these issues. A. Brazhnenko and etc. developed an insulation technology of absorbing horizons by non-solidified bitum-based and thermoplastic-based slurries with sulfur [1]. At the present time, the technology using composite based on polyethyleneterephthalate material is being developed by Yu. Kuzin and others [4]. The new efficient technology of elimination of the washing liquid absorption has been proposed in [5]. This one provides cryogenic (low temperature) freezing and plugging the borehole surrounding rock. The sketch of the process is shown in Fig. 1.

The authors [5] consider advanced technologies based on the use of phase transformation effects of plugging materials under the influence of thermal field. The proposed method allows:

- improving the quality of insulation of absorbing horizons for any degree of permeability, size, water content and spatial orientation of the absorption channels;

- providing the uniform distribution of crushing cement mixes in the absorbing horizon and improving the efficiency of the insulation screen quality.

The technological process consists of a number of operations (Fig. 1) including preparation of cementing material, its transportation to the bottom of a hole, pushing the mixture into horizon (formation of the insulating shell), and solidification of material period. The main difference in this technology is that the isolation process of passable horizon with plugging mixtures is performed under protection of cryogenic screen created in passable horizon with the low temperature technology.

It is necessary to note that the power consumption of the technology depends on thermophysical processes. Thus, to determine the rational technological parameters, namely, process duration and freezing-thawing depth of solid, it is necessary to study thermal processes in well surrounded massive.

Theoretical basis of calculation methods of heat transfer in wells have been developed by M. Pudovkyn, A. Salamatyn., V. Chuhunov. The development of these mathematical models allowed solving a number of applied problems regarding determination of thermal fields in the rock which surrounds the well considering the heat transfer of the rock and fluid flow in the well, for example [6, 7].

However, when solving the problem of freezing (thawing) of the rock mass it is necessary to solve the problem of heat conduction with phase transitions (Stefan problem), which in general has no analytical solution. In this way, numerical methods [8, 9] should be used to solve the problem. Nevertheless, as a first approximation, for the study of the formation process of the cryogenic screen under the refrigerant coolant influence it is possible to get an approximate analytical solution.

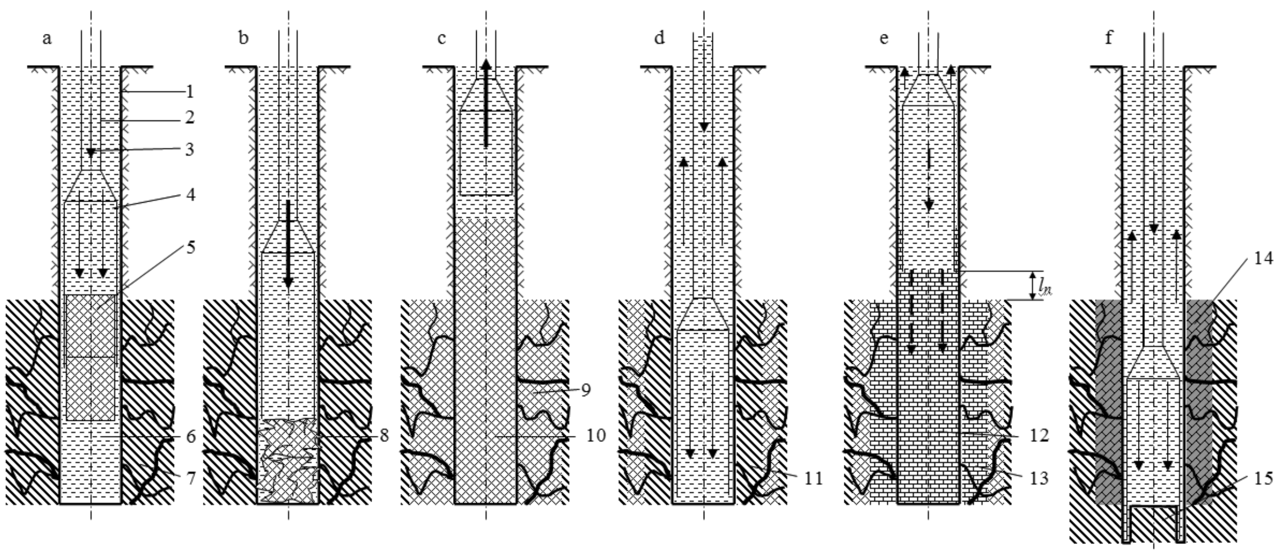

Fig. 1. Technology of absorptive horizons isolation:

a – delivery of refrigerant container to the well; b – the destruction of the containers; c – cryogenic screen formation in washing liquid absorption zone; d – drilling f ice-and-sand composite with further partitive thawing of permeable horizon; e – squeezing of plug-back mixture; f – drilling; 1 – the well wall; 2 – the drill string; 3 – the washing liquid; 4 – the core barrels; 5 – the refrigerant containers; 6 – the well; 7 – the absorptive horizon; 8 – destroyed containers; 9 – frozen horizon; 10 – frozen well bore; 11 – partitive thawed horizon; 12 – cementing slurry in well bore; 13 – cementing slurry in thawed zone of absorptive horizon; 14 – cement; 15 – core salvage

Objectives of the article. The aim is to develop procedure of calculating parameters of formation process of a protective inverted-cryogenic screen in the absorbing horizon of the borehole while applying the new innovative cryogenic technology of elimination of drilling fluid absorption.

Presentation of the main research. Let us consider the process of heat transfer in the rock massive which surrounds the well at the stage of the cryogenic screen formation (Fig. 1, *c*). The transfer process will be strictly in the radial direction and the rock is considered as the solid body with constant thermal properties in thawed and frozen layer. We neglect the phase transition heat. Rock freezing occurs because of reaction of refrigerant with temperature t_{cold} at the well wall. The temperature field in the rock which surrounds well will be described like this

$$\frac{\partial t}{\partial \tau}=a\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial t}{\partial r}\right),\quad a>0,\quad \tau>0,\quad R\le \tau<\infty; \qquad (1)$$

$$t\big|_{\tau=0}=t_0(z); \qquad (2)$$

$$t\big|_{r=R}=t_{cold}; \qquad (3)$$

$$\left.\frac{\partial t}{\partial r}\right|_{r\to\infty}=0, \qquad (4)$$

where t is rock temperature; τ is time; r is radial coordinate; a is thermal diffusivity of rock; R is well radius; t_0 is rock initial temperature which generally depends on the well depth z.

Let us introduce the dimensionless variables

$$\upsilon=\frac{t-t_{cold}}{t_0-t_{cold}};\quad \bar{r}=\frac{r}{R}, \qquad (5)$$

in this case we mean that $t_{cold}\le t_f< t_0$, where t_f is the temperature of liquid phase transformation. Also, let us introduce a dimensionless radius of temperature perturbation

$$l=f(\text{Fo}), \qquad (6)$$

where dimensionless time $\text{Fo}=\frac{a\tau}{R^2}$ (Fourier criterion). To calculate parameters of the rock freezing process it is necessary to determine the type of dependence (6). Problem (1–4) can be reformulated in dimensionless form using (5) and determining the thickness of the frozen layer (6)

$$\frac{\partial \upsilon}{\partial \text{Fo}}=\frac{1}{\bar{r}}\frac{\partial}{\partial \bar{r}}\left(\bar{r}\frac{\partial \upsilon}{\partial \bar{r}}\right),\quad 1\le \bar{r}<l(\text{Fo}); \qquad (7)$$

$$\upsilon\big|_{\text{Fo}=0}=1; \qquad (8)$$

$$\upsilon\big|_{\bar{r}=1}=0;\quad \upsilon\big|_{\bar{r}=l(\text{Fo})}=1;\quad \left.\frac{\partial \upsilon}{\partial r}\right|_{\bar{r}=l(\text{Fo})}=0. \qquad (9)$$

To solve the problem (7–9) the approach by M. Pudovkyn et al. was used. An approximate solution of the problem (7–9) in the interval $1\le \bar{r}<l(\text{Fo})$ is presented in the form

$$\upsilon=\begin{cases}\sum_{i=1}^{n} b_i(\text{Fo})f_i(\bar{r}), & 1\le \bar{r}\le l(\text{Fo})\\ 1, & \bar{r}>l(\text{Fo})\end{cases}, \qquad (10)$$

where $f_i(\bar{r})$ are linearly independent system of functions on the given interval, where $f_0 = 0$. Let us require that

$$\frac{1}{\bar{r}}\frac{\partial}{\partial \bar{r}}\left(\bar{r}\frac{\partial f_k}{\partial \bar{r}}\right)=f_{k-1},\quad k=1,2,3,\ldots; \qquad (11)$$

$$f_k\big|_{\bar{r}=1}=0. \qquad (12)$$

The following system of function $f_i(\bar{r})$ satisfies equation (11) with the condition (12)

$$f_1=\ln \bar{r};$$

$$f_2=\frac{1}{4}(\bar{r}^2\ln \bar{r}-\bar{r}^2+1);$$

$$f_3=\frac{1}{16}\left(\frac{1}{4}\bar{r}^4\ln \bar{r}-\frac{3}{8}\bar{r}^4+\bar{r}^2-\frac{5}{8}\right),$$

etc.

The integral transform

$$\theta_k=\int_1^l \bar{r}\, f_k(\bar{r})\upsilon(\bar{r},\text{Fo})d\bar{r}, \qquad (13)$$

is applied to equation (7). After calculating the integrals the system of equations is obtained

$$\frac{d\theta_k}{d\,\text{Fo}}=\theta_{k-1}-l\,f_k'(l),\quad k=1,2,3,\ldots \qquad (14)$$

The solutions of (14) are

$$\theta_k=\sum_{i=1}^{k}C_i\frac{\text{Fo}^{i-1}}{(i-1)!}-\sum_{i=1}^{k}\frac{l\,f_k'(l)}{(k-i+1)!}\text{Fo}^{k-i+1}. \qquad (15)$$

Limited $k = 1$ in expression (15)

$$\theta_1=-lf_1'(l)\text{Fo}+C, \qquad (16)$$

where C is integration constant, which can be found from the initial condition (8)

$$C(l)=\int_1^l r\,f_1(\bar{r})d\bar{r}=\frac{l^2}{2}f_1(l)-\frac{l^3}{4}f_1'(l)+\frac{1}{4}.$$

To determine b_i we use the last two terms in (10). Thus, system of equations is obtained

$$b_1f_1'(l)+b_2f_2'(l)=0;$$
$$b_1f_1(l)+b_2f_2(l)=1,$$

its solution gives two first values b_i

$$b_1 = \frac{-f_2'(l)}{f_1'(l)f_2(l) - f_2'(l)f_1(l)};$$

$$b_2 = \frac{f_1'(l)}{f_1'(l)f_2(l) - f_2'(l)f_1(l)}.$$

As can be seen, the approximate solution problem (7–9) in form (10) is defined up to the second term of the series. To determine the connection between the time of the freezing process and thickness of the frozen layer the first integral transform (13) and the solution (16) can be used. Taking into account (11) and (12) let us calculate integral (13) at $k = 1$

$$\begin{aligned}\theta_1 &= \int_1^l \bar{r} f_1(\bar{r})(b_1(l)f_1(r) + b_2(l)f_2(l))d\bar{r} = \\ &= b_1(l)\cdot l\cdot(f_1(l)f_2'(l) - f_1'(l)f_2(l)) - \\ &-b_2(l)\cdot l\cdot(f_1(l)f_3'(l) - f_1'(l)f_3(l)).\end{aligned} \quad (17)$$

The needed relation is obtained by equating (16) and (17)

$$\text{Fo} = -\frac{1}{f_1'(l)}\left[\begin{array}{c} f_2'(l) + b_2(l)\cdot l\cdot(f_1(l)f_3'(l) - \\ -f_1'(l)f_3(l)) - C(l)/l \end{array}\right]. \quad (18)$$

Solution (18) allows determining the approximate time of the freezing process required to form the inverted cryogenic screen with dimensionless thickness l. We will do research on heat transfer processes in the rock using these solutions (10) and (18). Fig. 2 shows the dynamics of temperature changes in rock radially from the well wall during the refrigerant works, calculated using (10).

To terminate a thickness of protective screen a dimensionless temperature of phase transformation has to be introduced

$$\upsilon_f = \frac{t_f - t_{cold}}{t_0 - t_{cold}}.$$

For example, if $t_{cold} = -100$ °C and $t_0 = 10$ °C, $t_f = 0$ °C, then $\upsilon_f = 0.91$. The crossing points of the line $\upsilon = \upsilon_f$ and

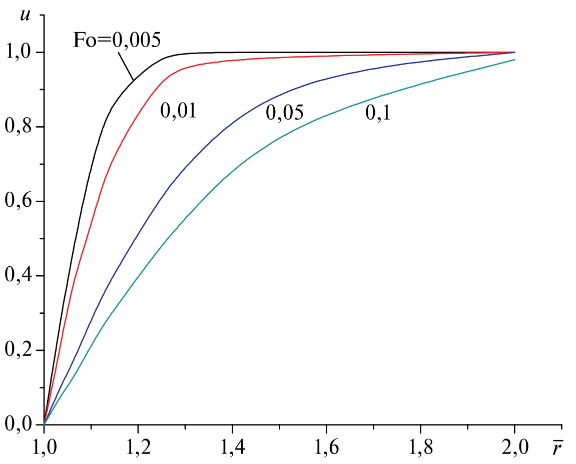

Fig. 2. Dependence of dimensionless temperature υ on dimensionless radius for different number Fo

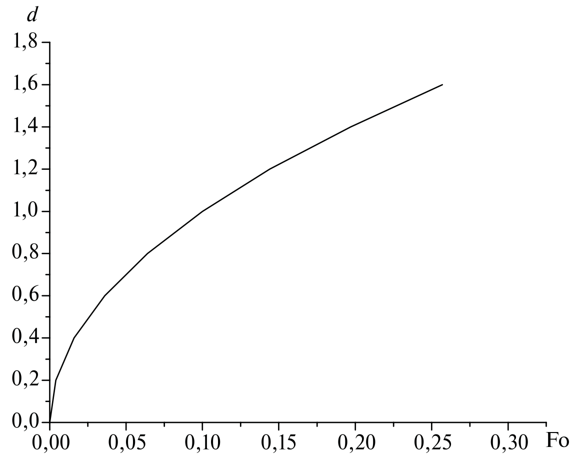

Fig. 3. The dependence of the cryogenic screen dimensionless thickness δ on Fo *values*

temperature curves give a thickness of protective screen δ.

The screen thickness change over time comes in accordance with (17) and is shown in Fig. 3.

So, expressions (10) and (17) can be used to estimate the parameters of technological process of the elimination technology of the washing liquid absorption.

Conclusions. We obtained an approximate analytical solution for the study of the processes of heat transfer in the rock during cryogenic screen formation around the well. We found regularity which connects freezing time of the rock with thickness of the cryogenic screen. The results can be used for validation of technological process of rock freezing during well isolation via new high efficiency low-temperature technology.

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Мета. Розробка методики розрахунку параметрів процесу формування захисного інверсно-кріогенного екрану в поглинаючому горизонті бурової свердловини при застосуванні інноваційної кріогенної технології ліквідації поглинання промивальної рідини.

Методика. Поставлені завдання вирішувалися із застосуванням аналітичних, експериментальних методів теплофізики й тепломасопереносу. Теоретичний аналіз – на основі аналітичного рішення задачі теплопереносу у промерзаючому напівнескінченому циліндричному шарі.

Результати. Здійснена фізична й математична постановка завдань. Розроблена математична модель і виконане теоретичне дослідження процесів теплопереносу у шарі гірської породи навколо свердловини за дії на стінці свердловини кріогенного (низькотемпературного) холодагенту. Представлена динаміка температурного поля в гірській породі та досліджена залежність часу процесу заморожування від потужності замороженого горизонту. Отримані аналітичні вирази для оцінки параметрів процесу формування захисного інверсно-кріогенного екрану в поглинаючому горизонті бурової свердловини.

Наукова новизна. Уперше встановлена залежність потужності інверсно-кріогенного екрану (замороженого шару гірської породи навколо свердловини) від тривалості процесу теплової обробки поглинаючого горизонту бурової свердловини й температури холодагенту.

Практична значимість. Розроблена інноваційна кріогенна технологія ліквідації поглинання промивальної рідини. Отримане аналітичне рішення процесу теплопереносу в гірській породі при формуванні інверсно-кріогенного екрану навколо бурової свердловини. Встановлена закономірність часу заморожування гірської породи від товщини інверсно-кріогенного екрану.

Ключові слова: *свердловина, ліквідація поглинання, кріогенна технологія, теплоперенос*

Цель. Разработка методики расчета параметров процесса формирования защитного инверсно-криогенного экрана в поглощающем горизонте буровой скважины при применении инновационной криогенной технологии ликвидации поглощения промывочной жидкости.

Методика. Поставленные задачи решались с применением аналитических, экспериментальных методов теплофизики и тепломассопереноса. Теоретический анализ – на основе аналитического решения задачи теплопереноса в промерзающем полубесконечном цилиндрическом слое.

Результаты. Осуществлена физическая и математическая постановка задач. Разработана математическая модель и выполнено теоретическое исследование процессов теплопереноса в слое горной породы вокруг скважины при действии на стенки скважины криогенного (низкотемпературного) хладагента. Представлена динамика температурного поля в горной породе и исследована зависимость времени процесса замораживания от мощности замороженного слоя. Получены аналитические выражения для оценки параметров процесса формирования защитного инверсно-криогенного экрана в поглощающем горизонте буровой скважины.

Научная новизна. Впервые установлена зависимость мощности инверсно-криогенного экрана (замороженного слоя горной породы вокруг скважины) от длительности процесса тепловой обработки поглощающего горизонта буровой скважины и температуры хладагента.

Практическая значимость. Разработана инновационная криогенная технология ликвидации поглощения промывочной жидкости. Получено аналитическое решение процесса теплопереноса в горной породе при формировании инверсно-криогенного экрана вокруг буровой скважины. Установлена закономерность, связывающая время заморозки горной породы с толщиной инверсно-криогенного экрана.

Ключевые слова: *скважина, ликвидация поглощения, криогенная технология, теплоперенос*

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