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# THEORETICAL BASES OF ISOLATION TECHNOLOGY FOR SWALLOWING HORIZONS USING THERMOPLASTIC MATERIALS

**Abstract.** The aim of the paper is to develop a general concept of a computational experiment for processes of heat-and-mass-transfer while eliminating the swallowing of washing liquid in a borehole using thermoplastic materials melts. Problems are set from the point of view of physics and mathematics. The general concept of the computational experiment is considered under theoretical modeling of processes of heat-and-mass-transfer in the elimination of washing liquid swallowing in a borehole. Theoretical foundations of swallowing horizons isolation using melts are developed, with an algorithm to make a software system allowing to calculate the heat-and-mass-transfer processes in a wide range of conditions. Practical value of the findings lies in the development of isolation technique for swallowing and unstable horizons, which requires the following technological operations: delivery of granulated thermoplastic material to the borehole bottom, local heating of the washing liquid, melting and squeezing of the thermoplastic material melt into the swallowing channels.

**Keywords:** drilling of the hole, swallowing horizon, thermoplastic materials, heat-and-mass-transfer.

**Introduction.** Technical-economic indicators of borehole drilling are mainly determined by time and costs spent on trouble-shooting. One of the most frequent troubles is swallowing of washing liquid. According to statistics, up to 20% of all the time and costs spent on borehole drilling are used to eliminate this problem. Swallowing leads to disturbances of process conditions of drilling, resulting in accidents.

Many researchers studied the formulation of washing liquids, plugging materials and methods to eliminate the swallowing of washing liquid. These studies were analyzed previously [1, 2].

The analysis shows that presently there are a number of various methods and materials used to eliminate and prevent the swallowing of washing liquid.

The swallowing of washing liquid can be prevented through regulation of washing liquid properties and reduction of pressure differential in the swallowing horizon [3, 4], whereas these methods are in a sense limited in applicability and in most cases are inefficient.

In the majority of cases, elimination of swallowing is fulfilled by plugging of channels swallowing the washing liquid by hardening or nonhardening plugging mixtures by means of creating a waterproof screen in the rock around the borehole. As a rule, to eliminate the swallowing of washing liquid, the used plugging materials are not sufficiently effective, being water-based and containing a mineral-cementing component or synthetic substances [4]. The main drawback of these materials is that they are very sensitive to water dilution – the solutions are easily mixed with washing liquid and stratal waters, especially in case of inter-reservoir communication. This results in dilution, sedimentation of plugging mixtures which leads to increased setting-up time, spreading across considerable area around the borehole, and as a consequence, to the overuse of plugging materials, and repeated plugging operations.

The above conclusions are confirmed in the findings provided in the research by Rafienko I.I., Titkov I.I., Mekhtiev E.H., Ivachev L.M. [1]. Ivachev L.M. points out in his paper that hardening plugging materials have an ultimate strength of plugging stone compared to the strength of permeable zone rocks, which results in effective swallowing elimination by plugging swallowing channels within the radius of dozens of centimeters or even centimeters.

To solve this problem, it is necessary to search for new methods based on different physical processes and alternative plugging materials that are water-insensitive. This includes the methods of isolation casing based on the use of aggregate state of the plugging material allowing to create an isolating casing around the borehole, which would be of low volume, durable and impermeable. This is why it is essential to develop an innovative method of swallowing horizons isolation, which would be based on the filling of swallowing channels with the fusible material melt.

**Problem statement.** In connection with this, plugging materials based on thermoplastic materials are of certain interest.

At the National Mining University (Dnipro city, Ukraine), the Department of Prospecting Methods of Mineral Deposits has conducted works on the development of non-traditional methods of plugging swallowing horizons. The developed methods allow to create low-volume impermeable membranes with the use of non-traditional plugging thermoplastic materials [5, 6] with low melting temperature, which easily invades into swallowing channels of washing liquid and solidifies there.

The rationale of the method lies in the creation of isolating membrane around the borehole (mine working) that is based on the change of aggregate state of the plugging thermoplastic materials non subject to dilution with ground waters, with a low melting point. Its melt permeates to the channels swallowing the washing liquid and solidifies there, thus creating low-volume reliable impermeable isolation membrane around the borehole.

Until now, only petroleum bitumen was used as a thermoplastic material. Among the main disadvantages of bitumen as a plugging material is its property of running down with time: under changing pressure of 0.3–0.5 MPa it can run down even at the temperature of $+15^0$C. Bitumen melt density is close to water density, thus in the washing liquid medium it can split and float. Bitumen is hard to drill out, and therefore it can clog a drilling tool. It is also known to have cancerogenic properties and adverse effect on the environment. Thus, resulting from these and other disadvantages, bitumen is not widely used as a plugging material.

Plugging materials used for swallowing horizons isolation should not shrink or crack when solidify, nor should they flow in cracks; they must have good adhesion with rock, as well as be water-insensitive and resistant to pressure changes. In addition, these materials must be one-component, be processible when delivered to the plugging zone, be easily drilled and washed from the drilling tool, and have a greater density than that of cleansing agent.

The analysis of previous research on the use of sulphur as permeant and binding material, as well as the study of its physical and mechanical properties, confirmed its potential applicability as a plugging material for isolation of swallowing horizons of boreholes.

Solid sulphur is chemically inert and is not affected to aggressive water. Sulphur is easily drilled and doesn't stick to the drilling tool. Storage stability of granulated sulphur doesn't affect its physical and mechanical properties. The cost of sulphur is comparable to the cost of concrete and is far lower than the cost of synthetic resins and bitumen. Thanks to the low melt viscosity of both pure sulphur and sulphur with plasticizing agent additives, it can easily penetrate into rock with insignificant crack opening displacement. The strength of plugging stone obtained after sulphur melt cooling is comparable to the strength of concrete stone, while in the early stage of solidification, the strength of sulphur is a sequence higher than that of concrete stone under unixial compression. The melting temperature of plugging thermoplastic material can be adjusted by the introduction of plasticizing agents [6].

**Statement of the main material.** The aim of the article is to consider theoretical basis of swallowing horizons isolation with the use of melts to build algorithms, to create a software package and methods allowing the computer-aided calculation of processes of heat-and-mass-transfer in a wide range of conditions.

A distinctive feature of this method is that thermoplastic material with low melting point is delivered to the trouble zone in the solid state, where it is melted to the liquid state by the bottom-hole heat source. At this, washing liquid in the borehole in the swallowing zone must be heated to the temperature higher than the melting point of the thermoplastic material. Possible ways of implementation of this method are presented in table.

Method of swallowing horizons isolation with thermoplastic materials

| Process steps | Possible ways of performing the operations |
|---|---|
| Heating of bottom-hole area | Fire |
| | Chemical |
| | Bottom-hole cabled electrical heater |
| Delivery of plugging material to the bottom hole | Along the borehole |
| | Along the pipe string |
| | In a container |
| Melting | By means of washing liquid heat |
| | By contact method |
| | In a container |
| Squeezing of the plugging material melt | Under the excess density of the melt |
| | By increasing the fluid column in the borehole |
| | By injection of fluid through sealed drill hole collar |

Thus, to realize the offered method, it is necessary to fulfill the following technological operations: delivery of the granulated thermoplastic material to the bottom-hole, local heating of the washing liquid in the area surrounding the borehole, melting and squeezing the melt of thermoplastic materials in the swallowing channels.

To heat thermoplastic material, one of the schemes of the offered method involves washing liquid in the borehole as a heat-transfer medium [6]. The heating of washing liquid in the borehole is realized by the bottom-hole electric heater in the same way as in electrothermal oil well treatment. To solve the practical problems in calculation of the time needed for the heating of washing liquid and thermoplastic material, temperature field, the radius of isolation membrane around the borehole and so on, it is necessary to study the processes of heat-and-mass-transfer in the swallowing horizon area.

Analytical studies of these processes can currently be conducted by means of computer-aided numerical modeling. This approach is also significant because the experimental study of these processes in the laboratory or field conditions is very complicated and expensive and in some cases impossible [7, 8].

Theoretical methods of study of heat transfer processes in the wells were developed by M. A. Pudovkin, A. N. Salamatin and V. A. Chugunov. Proposed mathematical models allow to determine temperature fields in the surrounding borehole rock taking to account heat exchange of the rock and fluid flow in the well. There are some examples of heat transfer problems in drilling engineering.

The work [9] is devoted to the study of temperature fields in existing producing wells, the mathematical formulation which leads to the necessity of solving the pair of equations of convective heat conduction with sources. To construct the exact solutions to such problems is possible only in rather simple cases. In this paper based on modified asymptotic method, the solution is reduced to the chain of boundary-value problems for the coefficients of the asymptotic expansion, which in the space of Laplace-Carson reduced to a sequence of ordinary differential equations. Unlike previous works of the authors, where the originals were built only for small and large times, in this work the construction of the originals is carried out numerically, which will significantly clarify the description of the temperature field in the borehole.

A general concept of computing experiment in theoretical modeling of processes of heat and mass transfer in the elimination of absorption of washing liquid in the well is developed. The theoretical foundations of the isolation of absorptive horizons using melts with the construction of an algorithm for creating a complex process of calculating the heat and mass transfer program with the use of computers in a wide range of conditions[10].

The mathematical model of heat transfer processes in cryogenic gravel filter was developed in work [11]. This model including a system of differential equations describing heat and mass transfer processes which take place during the technological operations. Propose model was used in work [12] to determinate several important parameters of technological operations when cryogenical gravel filters are applied.

The energy prediction theory of zonal capsulation parameters research of mine workings is developed which allows studying shapes, sizes, quantity and conditions of formation of energy zones and borders of possible destruction of the massif. Power dependences are established as to changing the sizes of adjacent power zones whose ratio is a constant from the sizes and shape, depth of laying and physical properties of massif containing mine working. The thermodynamic theory of massif that is not disturbed by workings is improved by means of considering the processes of geo-energy streams redistribution and entropy exchanging with allocation into undisturbed massif in a separate entropy method of research. Further development of the sinusoidal-fading dependence of auto-wave fluctuations of stresses in massif that broken by mine workings from gradients of density, temperature, gas and water saturation of rocks is given [13].

The paper considers the new technology plugging wells walls using freezing rock. The scheme of this technology is presented herein. It needed the investigation of temperature state of well surrounding rock massive to definite the rational parameters of the freeze impact. A mathematical model of heat transfer processes in rock massive under refrigerant impact was proposed. An approximate analytical method of calculation of temperature fields in the rock was developed. The research of the dynamics of rock temperature was conducted [14].

The novelty analysis of the thermal stressed condition of the rock formation was carried out 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 the 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 [15].

The ratio of zones vertical and horizontal semiaxes in the massif has been established and reliability of the obtained results was determined. The prospects of new modeling techniques for the study of massif zonal structuring parameters around underground workings have been identified. The opportunities for wide application of numerical simulation methods to study the phenomenon of zonal encapsulation by the massif of underground workings have been revealed. The sizes and shapes of zones in the massif around workings were determined and requirements were formulated stating that synergetic research methods should allow to more accurately determine the number, size and shape of zones, as well as fading sinusoidal stress and massif strain domains [16].

According to the offered method of swallowing horizons isolation using thermoplastic materials, the washing liquid is offered to be used as heat transfer medium heated by bottom-hole electric heater. The heating temperature of this heat transfer medium must be higher than the melting point of the thermoplastic material [10, 17].

In this case, with the given power of the electric heater, the problem boils down to the calculation of the necessary amount of operating time and temperature field in the trouble zone of the borehole.

Heat transfer from the stationary source located in the borehole is done through heat transfer and convection. It is taken into account that from the cylindrical heater with constant power, along with radial heat distributor, the heat is also dissipated into the roof and floor of the swallowing horizon. The strata is considered to be homogenous isotropic medium, heat constants of the strata of overburden and underlying bedrock are considered to be equal.

The heating of the heat transfer medium, in our case it is water, along with the big contact area results in an intensive thermal exchange between the water and the strata.

Suppose the radius of the source equals the radius of the borehole, and the axes of the source coincide with the axes of the borehole. Let's choose the following system of axes: the origin coincides with the source centre, z-axis – with the borehole axes, r-axis goes through the centre of the source (figure 1).

Find temperature distribution using the thermal conductivity equations for a symmetrical source with cylindrical coordinates.

$$\frac{\partial T_1}{\partial \tau} + \upsilon_z \frac{\partial T_1}{\partial z} = a_1 \left( \frac{\partial^2 T_1}{\partial r^2} + \frac{1}{r} \frac{\partial T_1}{\partial r} + \frac{\partial^2 T_1}{\partial z^2} \right), \quad \text{(I area)} \tag{1}$$

$$0 < r < R'; \quad Z'' < Z < Z'; \quad \tau > 0;$$

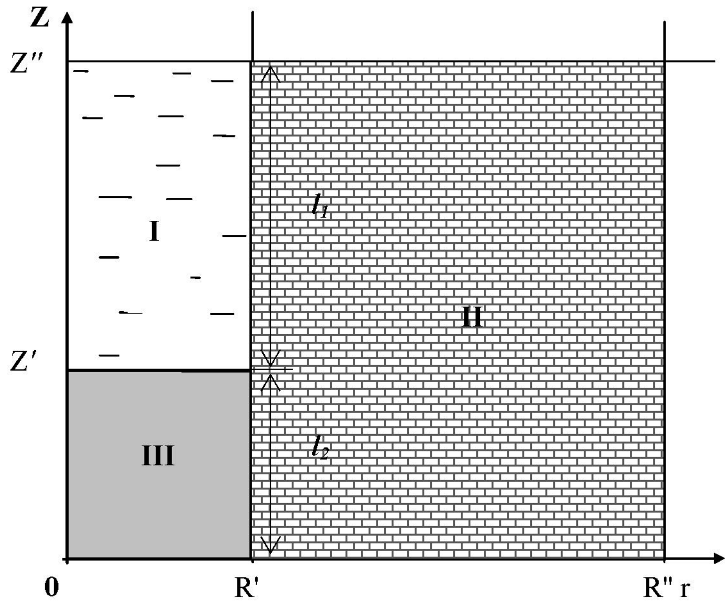


Figure 1 – Scheme to mathematical statement of the problem:
I – is the area of the heated heat transfer medium; II – is the area of the surrounding rocks; III – is the heater

$$\frac{\partial T_2}{\partial \tau} = a_2\left(\frac{\partial^2 T_2}{\partial r^2} + \frac{1}{r}\frac{\partial T_2}{\partial r} + \frac{\partial^2 T_2}{\partial z^2}\right), \quad \text{(II area)} \tag{2}$$

$$0 < Z < Z''; \qquad R' < r < R'';$$

with initial conditions:

$$T_1(r,z,0) = T_2(r,z,0) = T_0,$$

and boundary conditions:

by $r$

$$\left.\frac{\partial T_1}{\partial r}\right|_{r=0} = 0;$$

$$T_1\Big|_{\substack{r=R' \\ Z'<z<Z''}} = T_2\Big|_{\substack{r=R' \\ Z'<z<Z''}};$$

$$\lambda_1 \left.\frac{\partial T_1}{\partial r}\right|_{\substack{r=R' \\ Z'<z<Z''}} = \lambda_2 \left.\frac{\partial T_2}{\partial r}\right|_{\substack{r=R' \\ Z'<z<Z''}};$$

$$\left.\frac{\partial T_2}{\partial r}\right|_{r=R''} = 0;$$

$$\lambda_2 \left.\frac{\partial T_2}{\partial r}\right|_{r=R''} = -N;$$

by $z$

$$\left.\frac{\partial T_2}{\partial z}\right|_{z=0} = 0;$$

$$\left.\frac{\partial T_1}{\partial z}\right|_{z=z'} = 0;$$

$$\lambda_1 \left.\frac{\partial T_1}{\partial r}\right|_{z=Z'} = -N;$$

$$\left.\frac{\partial T_2}{\partial z}\right|_{z=Z''} = 0;$$

$$\left.\frac{\partial T_1}{\partial z}\right|_{z=Z''} = 0,$$

where $T_1, T_2$ – are temperature distribution, in areas I and II, respectively; $a_1, a_2$ – are thermal diffusivity coefficients of areas I and II, respectively; $\lambda_1, \lambda_2$ – conductivity coefficients of areas I and II, respectively; $c_1, c_2$ – is specific thermal capacitance of the borehole liquid and rock respectively; $N$ – is specific power of the source; $T_0$ – is some initial temperature in the rock and borehole liquid.

Calculation of the velocity of convectional current $\upsilon_z$ represents a rather challenging problem. As a first approximation, we will take it as a constant. We will use relation [7] for calculation

$$\upsilon_z = \sqrt{2g\beta\vartheta},$$

where g – is gravitational acceleration; $\beta$ – is the thermal coefficient of liquid expansion; $\vartheta$ – is the difference between initial liquid temperature and heater temperature.

Non-linear problems are usually not solved by the analytical method. To solve these problems, the numerical method can be utilized.

Among all numerical methods, the most widely used in solution of thermal conductivity problems is the method of finite differences (mesh method) [19, 20]. This is explained by the versatility of this highly algorithmic method, which opens wide range of possibilities to use modern computer applications. Mesh method allows maximum reflection of the specific character of the real process in the mathematical formulation of the problem and practically has no limits on the problem specification [17].

For this purpose, the algorithm of numerical calculation of the process of heating borehole liquid during isolation of swallowing horizon by thermoplastic materials was developed and realized using a computer application.

Under the given power of the electric heater, heat-transfer properties of the borehole liquid and rock of the swallowing horizon, the developed software allows determining the behavior of temperature distribution over the time and space (figure 2).

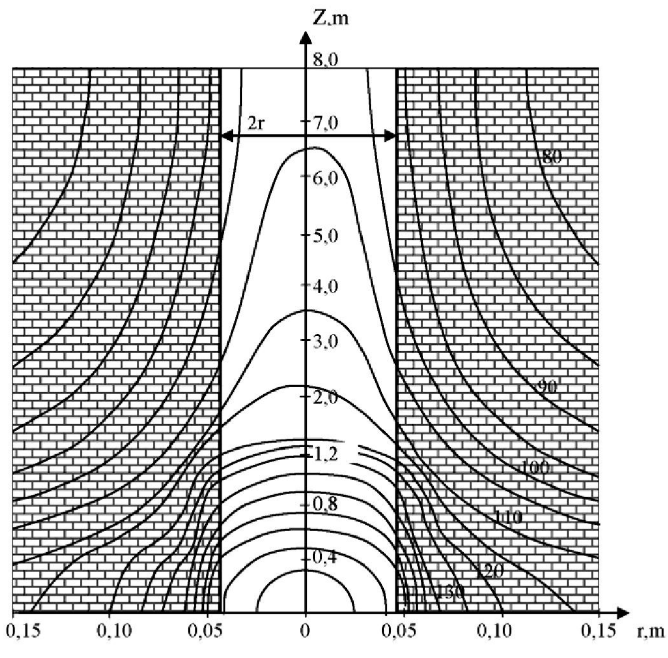


Figure 2 – The behavior of temperature field distribution in a borehole
with the diameter of 93 mm after 8 hours of operation of the electric heater with the power of 10 kWt

The results of the analytical study were confirmed by field study, as a result, relationship between the changes in the temperature of borehole liquid along the borehole axis in time was established (figure 3).

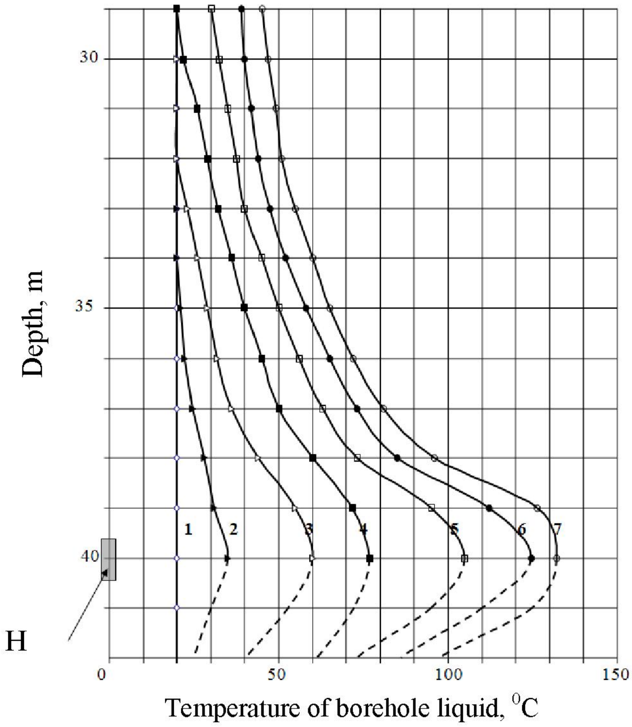


Figure 3 – Temperature distribution along the fluid column at:
1 – 0 min; 2 – 30 min; 3 – 60 min; 4 – 90 min; 5 – 120 min; 6 – 150 min; 7 – 180 min, H – electric heater

**Conclusion.** On the basis of analytical, bench, field and industrial research, is offered a new non-traditional method of isolation of swallowing horizons based on filling the swallowing channels with fusible materials melt.

Reliability of the results of numerical modeling is confirmed by the volume of the performed borehole studies, which guarantees the accuracy of the results and discrepancy with theoretical study within 10–15%.

The designed mathematical model of the temperature field allows to describe the process of heat transfer with the electric-thermal treatment of the borehole in the trouble zone. As a result, the differences in thermal-physical properties at the interface of two mediums (borehole liquid – rock) there occurs a significant temperature difference (figure 2). The developed software designed to calculate the parameters of temperature field allows choosing the optimal mode of heat-transfer medium heating in every specific case for different types of mediums, depending on the thermal-physical properties, to ensure minimal thermal losses.

The results of the theoretical study were confirmed during the laboratory tests and made the basis for the creation of sampler's practical design successfully tested in industrial conditions.

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## ТЕРМОПЛАСТИКАЛЫҚ МАТЕРИАЛДАРДЫ ҚОЛДАНУ АРҚЫЛЫ ЖАҺАНДЫҚ КӨКЖИЕКТЕР ҮШІН ОҚШАУЛАУ ТЕХНОЛОГИЯСЫНЫҢ ТЕОРИЯЛЫҚ НЕГІЗДЕРІ

**Аннотация.** Жұмыстың мақсаты термопластикалық материалдар қорытпаларын қолдану арқылы ұңғы оқпанында жуу сұйықтығының жұтылуын жою кезінде жылумассатасымалдау үрдістері үшін есептеу тәжірибесінің жалпы тұжырымдамасын дайындау. Жұмыс міндеттері физика және математика тұрғысынан қарастырылған. Ұңғы оқпанында жуу сұйықтығының жұтылуын жою кезінде жылумассатасымалдау үрдістерін теориялық модельдеу кезінде есептеу тәжірибесінің жалпы тұжырымдамасы қарастырылады. Жағдайлардың кең ауқымында жылумассатасымалдау үрдістерін есептеуге мүмкіндік беретін бағдарламалық жүйелерді құру алгаритмі бар қорытпаларды қолдану арқылы жұту көкжиектерін оқшаулаудың теориялық негіздері дайындалды. Нәтижелердің практикалық құндылығы жұтылуға және тұрақсыз көкжиектерге арналған оқшаулағыш техниканы дайындау, бұл келесі технологиялық операцияларды талап етеді: ұңғы түбіне түйіршіктелген термопластикалық материалдарды тасымалдау, жуу сұйықтығын жергілікті жылыту, жұту каналдарында термопластикалық материалдар қорытпаларын балқыту және сығу.

**Түйін сөздер:** ұңғыларды бұрғылау, жұтқыш көкжиек, термопластикалық материалдар, жылумассатасымалдау.

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## ТЕОРЕТИЧЕСКИЕ ОСНОВЫ ИЗОЛЯЦИОННОЙ ТЕХНОЛОГИИ ДЛЯ ГЛОБАЛЬНЫХ ГОРИЗОНТОВ С ИСПОЛЬЗОВАНИЕМ ТЕРМОПЛАСТИЧЕСКИХ МАТЕРИАЛОВ

**Аннотация.** Целью работы является разработка общей концепции вычислительного эксперимента для процессов тепломассопереноса при исключении проглатывания промывочной жидкости в стволе скважины с использованием расплавов термопластичных материалов. Задачи задаются с точки зрения физики и математики. Рассматривается общая концепция вычислительного эксперимента при теоретическом моделировании процессов тепломассопереноса при устранении проглатывания промывочной жидкости в стволе скважины. Разработаны теоретические основы изоляции глотационных горизонтов с использованием расплавов с алгоритмом создания программной системы, позволяющей рассчитать процессы тепломассопереноса в широком диапазоне условий. Практическая ценность результатов заключается в разработке техники изоляции для глотания и неустойчивых горизонтов, что требует следующих технологических операций: доставка гранулированного термопластичного материала на дно скважины, локальный нагрев промывочной жидкости, плавление и сжатие расплава термопластичного материала в каналы глотания.

**Ключевые слова:** бурение скважины, глотательный горизонт, термопластичные материалы, тепломассоперенос.