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Reductıon of thermal tensıons and temperatures formed ın the trıbonodes and surfaces of the equıpment and tools used ın well workover and restoratıon works

Zmniejszenie naprężeń termicznych i temperatur wytwarzanych w węzłach tarcia oraz powierzchniach urządzeń i narzędzi używanych do rekonstrukcji i renowacji odwiertów

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ABSTRACT: The maintenance of equipment and tools used in the workover of oil and gas wells depends on keeping them in good working condition, maintaining the reliability, strength, and temperature endurance of the tool. To restore wells after an accident and bring them back into operation, it is necessary to speed up the drilling and repair work by choosing the right repair equipment and following the existing rules and regulatory documents. The cutting elements of tools working under high pressure and loads are deformed, a tense situation is created in the cutting – a destruction zone and high temperatures (1000–1200°C) occur because of corrosion in the triboknots. The stress-deformation state in the cutting-destruction zone causes the formation of microcracks in the working area of the tool. Microcracks grow after a certain period. Cutting elements are quickly worn, in some cases break and fail quickly. Such cases affect the structural composition of the cutting elements, an increase in temperatures; as a result, riveting occurs. In order to keep the equipment and tools used in the repair in normal working condition, adjusting the mode parameters is one of the important requirements, in addition to taking special care of them. Optimum results obtained in repair and restoration depend on the efficiency of the cutting-destructive tool, longevity, material selection, construction manufacturing technologies, tools that meet modern requirements, dimensions, weight, and internal condition of the well being restored. It is necessary to keep the heat generated in the moving parts of the tool at the required level for the safe performance of restoration work. The thermal regime of cutting and rock-destroying tools depends on the physical-mechanical properties of the objects subjected to destruction, and the effect of thermomechanical stresses generated on the contact surfaces of the tool and the amount of heat released from the working surface. Studying the problems related to heat issues will ensure the temperature tolerance of not only the repair equipment, but also the equipment and tools used in other areas of the oil-field industry.

Key words: temperature, cutting and destructive tool, metal, rock.

STRESZCZENIE: Utrzymanie urządzeń i narzędzi używanych w rekonstrukcjach odwiertów ropy i gazu zależy od zachowania ich w stanie gotowości do pracy, niezawodności, wytrzymałości oraz trwałości temperaturowej narzędzia. Aby przywrócić odpowiedni stan odwiertów po awarii oraz ponownie rozpocząć ich eksploatację trzeba przyspieszyć prace wiertnicze i naprawy poprzez wybranie właściwych urządzeń naprawczych oraz przestrzeganie istniejących przepisów i dokumentów regulacyjnych. Elementy tnące narzędzi pracujących pod wysokim ciśnieniem i obciążeniami ulegają deformacji, wytwarza się sytuacja naprężenia w strefie tnąco-niszczącej i występują wysokie temperatury (1000–1200°C) w wyniku korozji w węzłach tarcia. Stan naprężenie-odkształcenie w strefie tnąco-niszczącej powoduje tworzenie mikropęknięć w obszarze roboczym narzędzia. Mikropęknięcia propagują po pewnym czasie. Elementy tnące szybko się zużywają, w niektórych przypadkach szybko pękają i ulegają awarii. Takie przypadki wpływają na skład strukturalny elementów tnących, wzrost temperatury i w rezultacie następuje unieruchomienie. Aby utrzymywać urządzenia i narzędzia używane przy naprawie w normalnych warunkach roboczych, jednym z najważniejszych wymogów jest dostosowanie parametrów trybu pracy, oprócz objęcia ich specjalną uwagą. Dobre wyniki uzyskane w robotach naprawczych i renowacyjnych zależą od sprawności narzędzia tnąco-niszczącego, trwałości, doboru materiałów, technologii produkcji konstrukcji, narzędzia spełniającego nowoczesne wymagania, jego wymiarów, wagi oraz stanu wewnętrznego odwiertu podlegającego renowacji. Dla bezpiecznego wykonania prac renowacyjnych konieczne jest utrzymanie ciepła generowanego w częściach ruchomych narzędzia na wymaganym poziomie. Reżim cieplny narzędzi tnących i niszczących skałę zależy od właściwości fizyko-mechanicznych obiektów podlegających niszczeniu i efektu naprężeń

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termomechanicznych generowanych na powierzchniach kontaktowych narzędzia oraz od ilości ciepła uwolnionej z powierzchni roboczej. Badanie problemów związanych z zagadnieniami ciepła pozwoli na zapewnienie tolerancji temperaturowej nie tylko urządzenia naprawczego, ale również urządzeń i narzędzi używanych w innych dziedzinach przemysłu złóż ropy.

Słowa kluczowe: temperatura, narzędzie tnące i niszczące, metal, skała.

Introduction

In the well workover, during the technological operation inside the well and during the destruction of rocks, the temperatures separated from the surface during heat conduction and convective heat exchange on the touching surfaces of cutting elements in the reinforced area and the deformation-stress state on the touching surfaces lead to an increase in stress.

The study of the regularities of heat transfer processes will serve to reduce thermal stress on the contact surfaces of metals and other alloy compounds where the cutting part of the tool is reinforced. Studying the regularities of heat conduction is one of the important issues in solving problems related to temperatures.

In the analytical solution of problems related to heat transfer, objects are considered as a whole. Considering heat transfer coefficients, heat transfer is aimed at reducing temperatures on the touching surfaces of the tool, reducing temperature stress in the working areas of the tool (Mustafayev and Nasirov, 2022).

The main reason for the introduction of new modern technical means and technologies for drilling and milling in the wellbore is mainly related to the study of temperature factors, which is currently of great importance. High temperatures on the destructive and cutting surface of drilling and repair equipment lead to emergencies. One of these situations can be attributed to the sticking of the cutting edge, which occurs most often. Subsequently, approximately 10–12% of the total time is spent on eliminating sticking.

The efficiency of drilling equipment is directly related to ensuring the temperature regime in the destruction zone of rocks with different physical and mechanical properties (Neskoromnykh and Popova, 2018b).

The influence of the temperature factor and the wear resistance of drilling equipment is noticeable when using low-heat-capacity and heat-conducting cleaning and flushing agents, such as compressed air and other aerated liquids. As a result of the research, it was found that unpleasant conditions occurred when the drilling tool was cooled during the drilling of a well, when air was blown with a small mass flow rate, density and specific heat, the values of which are approximately four times lower than that of water. It was found that when the cutting bit was cooled, blowing with air at a low mass flow rate became worse than when blowing with a gas-liquid agent. The research results show that the normalization of work when drilling wells with a rock-destroying tool with blowing is possible by expanding the channels and annular gaps through which air passes. It is possible to achieve a significant decrease in temperature with forced cooling by increasing the air flow at its low speeds (Neskoromnykh and Popova, 2018b).

When the destructive tool is heated at a shallow depth of the well in the end part of the annular bit, the average temperature can be taken from all individual parts of the temperature field currently developing in carbide cutters (Neskoromnykh, 2015).

For carbide crowns, the temperature confirmed experimentally has a real value (Tretyak et al., 2017).

The temperature is mainly influenced by such factors as the consumption and movement mode of the flushing fluid, heat transfer coefficients between the bit and the core, the thermal conductivity of the bit material, the power developed at the bottomhole, the temperature of the flushing and blowing agent for cleaning the bottomhole, the design dimensions of the destructive bit, as well as the properties of the material and penetration of the rock (Salikhov et al., 2006).

When drilling with a 93 mm carbide bit in sandstones with positive bottomhole temperatures, using basic cleaning agents such as water, normal mud and air, the actual air density at a depth of 100 meters was considered. The dependence of the temperature at the end of the annular crown on the air flow was also determined. With an increase in flow rate over 3–4 m^3/min, the temperature drop at the end slows down and at the same time the pressure loss in the well circulation system occurring due to air leakage through the joint leakage and due to energy consumption for the compressor drive increases. Air supply above 4 m^3/min is superfluous without changing the geometry of the cutting crown, since in this case the stagnation temperature increases (Kudryavtsev, 2003).

When developing the design of the cutting bit of a rock-destroying tool, special attention is paid to temperature processes that affect the progress of well drilling. To study the temperature processes on the contact surface of the rock-destructive tool with rock, a simultaneous investigation of thermal and hydraulic phenomena occurring during drilling and milling is conducted. Experimental studies of temperature processes are difficult and do not allow direct measurements at the source of heat generation. Simulation of the drilling process will allow the temperature inside the cutter body to be measured. At the same time, the system makes it possible to take such a part of the crown as the basis of the simulation model, which reliably considers the symmetry of the ongoing processes and significantly reduces research resources. In this case, the boundaries of the model are defined by symmetry planes, and these are within the area of the crown sector, passing through the centre of the flushing holes. To develop a new design of rock-breaking and milling tools that meet modern requirements, it is necessary to conduct a reliable study of their work on an experimental device simulating well conditions using progressive innovative approaches (Proselkov et al., 1973).

In order to design the optimal design, the proposed example of studying the operation of a cutting and rock-breaking tool bit shows that well drilling is a complex system for modelling; therefore, scientific research on drilling and milling processes should be based on an integrated approach.

In permafrost rocks, the flushing liquid should have a minimum heat capacity and thermal conductivity. The temperature of the drilling fluid should not be lower than the temperature of the rocks being drilled (Bondarev and Krasovitsky, 1974; Proselkov, 1975; Kudryashov and Yakovlev, 1983).

The intensity of heat exchange between the descending and ascending flows plays a decisive role influencing the nature of the solution temperature distribution in the well during drilling.

Thermal calculations make it possible to find the temperatures of the rocks around the well or the temperature of the well production (Proselkov, 1975; Ermilov et al., 2003; Kudryavtsev, 2003; Polozkov, 2009; Timofeev et al., 2015).

The analytical calculations carried out are reduced to the fact that the temperature of the rocks around the well is taken as the boundary conditions, the result of the solution is the temperature of the oil, and the solution determines the temperature field in the rocks. This one-sided task is often used in practical calculations.

In the process of drilling, the temperature regime of the well changes all the time. For this reason, it is necessary to solve an important problem – the determination of the time required for the transition of an unsteady process to a steady one. A direct indicator of the end of such a transition is the onset of the temperature stability of the flushing liquid.

In many of heat transfer tasks, Stefan's statement is used, in which phase transitions occur in rocks at 0°C, and in Kolesnikov's statement that they occur in a certain temperature range. Kolesnikov's statement is more complicated; therefore, Stefan's statement is often used in heat transfer problems. According to this method, the temperature and heat flux at each point were determined from a stationary solution. The solution of the problem by the Stefan method leads to an ordinary differential equation for phase separation as a function of time. Basically, the tasks were solved using two systems of equations: the heat influx equation for the oil flow in the well and the Stefan conditions – a non-stationary heat influx equation that allows the rate of temperature drop along the oil or gas wellbore to be estimated. The task of determining the temperature distribution in the wellbore and the thawing configuration at different times was theoretically solved. However, the thawing around the well is solved in a one-dimensional formulation of the problem; that is with a change in temperature only in the radial direction. The well is quite an extended object, with a sufficient degree of accuracy. Several problems were formulated, such as plane axisymmetric ones, in which only approximate solutions of the Stefan problem are given (Proselkov, 1975; Proselkov et al., 1973; Kudryashov and Yakovlev, 1983).

In many problems in the plane-radial formulation, vertical heat fluxes are not considered, which makes it possible to simplify the problem. Under these conditions, Fourier conditions are mainly used to determine the thawing radius around the well (Kudryashov and Yakovlev, 1983; Kudryavtsev, 2003; Salikhov et al., 2006; Timofeev et al., 2015).

In some works, the temperature regime of oil and gas wells is considered in a quasi-stationary approximation. To determine the temperature, a first-order ordinary differential equation is obtained from the energy conservation equation for the oil flow.

Under constant external conditions that determine the operation mode of the well-reservoir system, non-stationary heat transfer processes in the injection well are relatively short-lived. Therefore, the thermal regime of the well can be considered quasi-stationary.

A model of heat exchange between a well and rocks, in which the substantial posting in the energy equation for oil flow is neglected, in the proposal that the temperature in the well equalizes much faster than the temperature field changes in the rocks of the well (Ermilov et al., 2003).

The stationary equation of heat influx is more important for detailing the study of the two-phase nature of the coolant than considering non-stationary processes or heat exchange with surrounding rocks (Proselkov et al., 1973; Kudryashov and Yakovlev, 1983).

In the problems under consideration, the authors considered only one-dimensional problems, which do not make it possible to solve global issues in the study of heat generation during drilling and milling in the wellbore.

Novelty of the work

The calculation of the geometric dimensions (radius) of the cutting crown and the time of destruction of a single-cone bit were selected, as an example, to study the thermal stresses flowing in the fracture zone.

A theoretical analysis was carried out considering the geometric dimensions, and as a result, the dependence of temperature on time and the radius of increase along the periphery of the cutting edge was established.

Differential dependences and their boundary conditions are found when calculating the temperature of the cutting crown of the rock of the destructive tool in the process of drilling and milling. The calculations were carried out using the MS-EXCEL-2016 software. The results showed that as the radius increases along the periphery of the cutting bit, the temperature increases. Depending on time, the temperature first increases, and then gradually passes to a stationary regime.

Discussion

Well drilling is a complex system consisting of mechanical, chemical, hydraulic, and thermal processes. Previous studies in the field of drilling and milling show that the systems of equations proposed by the authors are quite significant and do not contribute to the efficiency of solving thermal calculations. There are no practical methods for solving related problems when the temperature in the well and in the rocks is simultaneously determined. The difficulty of solving temperature issues lies in the mathematical complexity of solving the adjoint problems of heat transfer between the bodies of the destroying and drilled object during the circulation of the convective agent. The study of the drilling and milling process is a complex task, and it is not always possible to solve them by conventional methods. In this direction, the most promising solution is modelling, which can bring the study model as close as possible to real conditions, reduce the time and cost of developing the cutting edge of the tool, and visually obtain the results of the analysis during the drilling process.

Task setting

Determination of differential equation writing, taking into account boundary conditions, which ensure reduction of temperatures generated in tribonodes and contact areas of equipment and tools used in repair and restoration works.

Task solution

To achieve the solution of the task, the effect of the temperatures generated on the surface of roller bit of milling type is considered.

The temperatures generated on the supports and touching surfaces of the tool depend on the mode parameters, the physical and mechanical properties of the objects exposed to the cutting, and the dimensions of the structure (Lykov, 1978; Osipova, 1979; Ametistova et al., 1982).

In real conditions, since the surface of a tool with a cone is cylindrical, its rotation radius is taken as the equivalent radius and the mass of the cone is determined as follows.

$$m = \frac{4}{3}\pi\rho(R^3 - r_0^3) \tag{1}$$

where:
m – is the mass of the cone,
ρ – is the density of the material of the cone,
R – is the outer radius of the cone,
r_0 – is the inner radius of the cone.

The heat equation for cylindrical bodies is expressed as follows:

$$\frac{\partial \Delta T}{\partial t} = \alpha\left[\frac{2}{r}\frac{\partial \Delta T}{\partial r} + \frac{\partial^2 \Delta T}{\partial r^2}\right] \tag{2}$$

$$\Delta T = T_{(r,t)} - T_0 \tag{3}$$

where:
T_0 – are the starting temperatures, when $T_0 \rightarrow t$, $T_0 \rightarrow t = 0$. For this reason, $t = 0 \Rightarrow \Delta T_{(r,0)} = 0$.

Since the initial condition T_0 is constant for the given conditions, if to consider expression (3) and (2), then:

$$\frac{\partial T_{(r,t)}}{\partial t} = \alpha\left[\frac{2}{r}\frac{\partial T_{(r,t)}}{\partial r} + \frac{\partial^2 T_{(r,t)}}{\partial r^2}\right] \tag{4}$$

where:
α – is the heat transfer coefficient.

$$\alpha = \frac{\lambda}{\rho c} \tag{5}$$

where:
λ – the heat conducting coefficient,
ρ – the density of the material,
c – the specific heat capacity.

In order to simplify the expression (4), it is necessary to choose such function "U" that has the form $U = r \cdot T_{(r,t)}$.

If we consider the function U in expression (4), then (Isayev et al., 1979):

$$T_{(r,t)} = \frac{U}{r}$$

$$\frac{\partial}{\partial t}\left(\frac{U}{r}\right) = \alpha\left[\frac{2}{r}\frac{\partial}{\partial r}\left(\frac{U}{r}\right) + \frac{\partial^2}{\partial r^3}\left(\frac{U}{r}\right)\right] \tag{6}$$

From (4):

$$\frac{1}{r}\frac{\partial U}{\partial t} = \alpha\left(\frac{2}{r}\left(\frac{1}{r}\frac{\partial U}{\partial r} - \frac{U}{r^2}\right) + \frac{1}{r}\frac{\partial^2 U}{\partial r^2} - \frac{2}{r^2}\frac{\partial U}{\partial r} + \frac{2U}{r^3}\right) \tag{7}$$

If we simplify the expressions in brackets, then we get:

$$\frac{1}{r}\frac{\partial U}{\partial t} = \alpha\frac{1}{r}\frac{\partial^2 U}{\partial r^2} \tag{8}$$

From here:

$$\frac{\partial U}{\partial t} = \alpha \frac{\partial^2 U}{\partial r^2} \quad (9)$$

The expression $U = r \cdot T_{(r,t)}$ varies within the limits $(0 \le r \le R)$:

1. $r = 0 \quad \rightarrow \quad U = 0$
2. $t = R \quad \rightarrow \quad U = R\,T_{(R,t)}$
3. $t = 0 \quad \rightarrow \quad U = f_{(r)}$

Under conditions 1 and 2 in the expression $U = r\,T_{(r,t)}$, when $t = 0$, then $T_{(r,t)} = T_{(r,0)}$ and $U = r\,T_{(r,0)}$.

That is, the function U becomes a function that depends only on r. This function is also called f_v function.

According to the 1st condition we accept U as $U = A_n \sin\frac{n\pi r}{2R}$, then since $r = 0$:

$$U = A_n \sin 0° = 0 \quad (10)$$

In the general case, one can choose such function that satisfies the 2nd and 3rd conditions. For this, it must be considered that U depends on both r and f.

Summarizing the obtained results, the following equation can be obtained:

$$U = g_{(t)} A_n \sin\frac{n\pi r}{2R} \quad (11)$$

$g_{(t)}$ is a function that depends on t, when $t = 0$ according to the 3rd condition, $g_{(0)} = 1$.

The explanation of A_n and n will be given with the Fourier series.

Based on equation (11), we can write the following special derivatives:

$$\frac{\partial U}{\partial t} = A_n \sin\frac{n\pi r}{2R}\frac{\partial g_{(t)}}{\partial t} \quad (12)$$

and

$$\frac{\partial^2 U}{\partial r^2} = -\frac{A_n n^2 \pi^2 g_{(t)}}{4R^2}\sin\frac{n\pi r}{2R} \quad (13)$$

If instead of (11) we write expressions (12) and (13), then we obtain:

Note: since the $g_{(t)}$ is a function that depends only on t, we can obtain its special differential with relation to t as an ordinary differential, i.e.:

If we write $\partial g_{(t)}/\partial t$ as $dg_{(t)}/dt$ the following is obtained (Peletsky et al., 1971):

$$\frac{\partial U}{\partial t} = \alpha \frac{\partial^2 U}{\partial r^2} \quad (14)$$

$$A_n \sin\frac{n\pi r}{2R}\frac{dg_{(t)}}{dt} = -\alpha\frac{A_n n^2 \pi^2 g_{(t)}}{4R^2}\sin\frac{n\pi r}{2R} \quad (15)$$

If we divide $A_n \sin(n\pi r/2R)$ in (15) on each side, then:

$$\frac{dg_{(t)}}{dt} = -\frac{\alpha n^2 \pi^2}{4R^2} g_{(t)} \quad (16)$$

$$\frac{dg_{(t)}}{dt} = -\frac{\alpha n^2 \pi^2}{4R^2} \quad (17)$$

If we integrate both sides of (17), then the following result is obtained:

$$\ln(g_{(t)}) = -\frac{\alpha n^2 \pi^2 t}{4R^2} + c(\mathrm{c}-) \quad (18)$$

$$g_{(t)} = e^{c - \frac{2n^2\pi^2 t}{4R^2}} = e^c e^{-\frac{\alpha n^2 \pi^2 t}{4R^2}} \quad (19)$$

Since the expression e^c is constant ($e^c + 0$), then it's possible to substitute this expression to c.

If we write e^c as c in (15), then:

$$g_{(t)} = c e^{-\frac{\alpha n^2 \pi^2 t}{4R^2}} \quad (20)$$

If we consider expression (20) in (11), then:

$$U = cA_n e^{-\frac{\alpha n^2 \pi^2 t}{4R^2}} \sin\frac{n\pi r}{2R} \quad (21)$$

The expression $A_n \sin(n\pi r/2R)$ corresponds to the n_{th} element of the Fourier series. The variable n is an expression, which varies from 1 to $+\infty$, indicating the order of the elements in the sequence. If we generalize the Fourier series, then the expression (21) is written as follows (Ustyuzhanin et al., 1985; Zorin, 2001):

$$U = \sum_{n=1}^{\infty} a_n e^{-\frac{\alpha n^2 \pi^2 t}{4R^2}} \sin\frac{n\pi r}{2R} \quad (22)$$

If we take b as $= \frac{\alpha \pi^2}{4R^2}$, then:

$$U = \sum_{n=1}^{\infty} a_n e^{-n^2 bt} \sin\frac{n\pi r}{2R} \quad (23)$$

Note:

1. The reason that n starts from 1 is that $\sin 0° = 0$. For $n = 0$. Therefore, the value of "n" is taken from 1 to $+\infty$.
2. The main reason why the constant c in the expression (21) is in (23) is that the expression a_n in the series also includes the constant c. For this reason, there is no need to use the constant c. Then the expression (23) is examined according to the boundary and initial conditions:

   2.1. $r = 0$;

   If to replace the condition $r = 0$ in the expression (23), then since $\sin 0° = 0$, $U = 0$, which satisfies the condition is obtained.

   2.2. $r = R$;

   If we consider the condition $r = R$ by a similar rule in (23), then:

$$U = \sum_{n=1}^{\infty} a_n e^{-n^2 bt} \sin\frac{n\pi r}{2R} \text{ here } \left(b = \frac{\alpha \pi^2}{4R^2}\right) \quad (24)$$

As can be seen from (24), expression (23) depends only on t due to the condition $r = R$.

2.3. $t = 0$;

If we consider the condition $t = 0$ in (23), then the function "U" is written as follows:

$$U = \sum_{n=1}^{\infty} a_n \sin\frac{n\pi r}{2R} (e^0 = 0) \tag{25}$$

Thus, expression (23) satisfies to all 3 conditions.

Since $U = r\, T_{(r,t)}$, then:

$$T_{(r,t)} = \sum_{n=1}^{\infty} a_n e^{-n^2 bt} \sin\frac{n\pi r}{2R} \tag{26}$$

Note:

Since 1/0 is undefined, the variable r is taken within the interval $0 < r \leq R$.

In expression (3), T_0 is the initial temperature, according to condition (3): $t = 0$; $T_{(r,t)} \Rightarrow T_{(r,0)} = T_0$ then:

$$T_0 = \frac{1}{r}\sum_{n=1}^{\infty} a_n \sin\frac{n\pi r}{2R} \Rightarrow rT_0 = \sum_{n=1}^{\infty} a_n \sin\frac{n\pi r}{2R} \tag{27}$$

To determine a_n from (27), each side of the equation is multiplied to the expression $\sin(k\pi r/2R)$:

$$rT_0 \sin\frac{k\pi r}{2R} = \frac{1}{r}\sum_{n=1}^{\infty} a_n \sin\frac{n\pi r}{2R}\sin\frac{k\pi r}{2R} \tag{28}$$

If we take x as $x = \pi r/2R$, then:

$$\frac{2RT_0 x}{\pi}\sin(kx) = \sum_{n=1}^{\infty} a_n \sin(kx)\sin(nx) \tag{29}$$

If we integrate both sides of (29) from negative ($-\pi$) to positive (π), then the following result is obtained:

$$\frac{2RT_0}{\pi}\int_{-\pi}^{\pi} x\sin(kx)dx = \sum_{n=1}^{\infty}\int_{-\pi}^{\pi} a_n \sin(kx)\sin(nx)dx \tag{30}$$

Let's consider both sides of (30) separately.

First, let's solve the integral on the right side of the equation:

Since a_n is a constant, it will appear in front of the integral.

Then it is sufficient to solve the following integral:

$$\int_{-\pi}^{\pi}\sin(kx)\sin(nx)\,dx = \frac{1}{2}\int_{-\pi}^{\pi}\big(\cos(k-n)x - \cos(k+n)x\big)dx \tag{31}$$

The number n can take any value from 1 to ∞.

Because $n = k$ at a certain stage, according to the states of n and k, two cases are possible at this time:

1. When $k = n$: $k - n = 0 \Rightarrow \cos(k-n)x = 1$ then:

$$\frac{1}{2}\int_{-\pi}^{\pi}[1-\cos(2nx)]dx = \frac{1}{4}\left(2x - \frac{1}{n}\sin(2nx)\right)\Bigg|_{-\pi}^{\pi} = \pi \tag{32}$$

Therefore, the right side of expression (32) will be $a_n\pi$.

2. If $k \neq n$:

$$\frac{1}{2}\int_{-\pi}^{\pi}[\cos(k-n)x - \cos(k+n)x]dx =$$

$$= \frac{1}{2}\left[\frac{\sin(k-n)x}{k-n} - \frac{\sin(k+n)x}{k+n}\right]_{-\pi}^{\pi} = 0 \tag{33}$$

Therefore, for the right side n has to be equal to k. Only in this case the integral on the right-hand side takes a non-zero value.

Let's consider the integral on the left side of E_q:

Since $2/\pi$, R, T_0 are constants, we exclude them from the integral. Then it'll be possible to solve the following integral.

$$\int_{-\pi}^{\pi} x\sin(kx)dx \tag{34}$$

When calculating the integral on the right-hand side, the integral can only be solved when $k = n$. Therefore, when calculating the integral on the left side, $k = n$ is considered (Shashkov et al., 1973; Vagaftik et al., 1978).

Thus:

$$\int_{-\pi}^{\pi} x\sin(nx)dx = \frac{1}{n^2}[\sin(nx) - nx\cdot\cos(nx)]_{-\pi}^{\pi} =$$

$$= -\frac{2\pi}{n}\cos n\pi \tag{35}$$

Then, on the left side:

$$-\frac{4RT_0}{n}\cos n\pi \tag{36}$$

If we replace the found expressions (33) and (36) (the integrals of the right and left sides of the equation) in the expression (30), then we get:

$$-\frac{4RT_0}{n}\cos(n\pi) = \pi a_n \Rightarrow a_n = -\frac{4RT_0}{n\pi}\cos(n\pi) \tag{37}$$

If we consider the expression (37) found for a_n in the expression (23), then the following equation is obtained:

$$T_{(r,t)} = -\frac{4RT_0}{r\pi}\sum_{n=1}^{\infty}\frac{\cos(n\pi)}{n}e^{-n^2 bt}\sin\frac{n\pi r}{2R} \tag{38}$$

Since solution of $\cos(n\pi)$ is only within the values –1 and +1:

$$\cos(n\pi) = (-1)^n \tag{39}$$

If we consider (39) in (38), then:

$$T_{(r,t)} = -\frac{4RT_0}{r\pi}\sum_{n=1}^{\infty}\frac{(-1)^n}{n}e^{-n^2 bt}\sin\frac{n\pi r}{2R} \tag{40}$$

* If we consider $r = R$ as a special case, then expression (36) becomes a function depending only on t, the following is obtained.

$$\sum_{n=1}^{\infty}\frac{(-1)^n}{n}r^{-n^2 bt}\sin\frac{n\pi r}{2R} \tag{41}$$

After performing some mathematical transformations for the expression, the following expression is obtained:

$$T_{(t)} = -\frac{4T_0}{\pi}\sum_{n=1}^{\infty}\frac{(-1)^n}{2n-1}\cdot e^{-(2n-1)^2 bt} \tag{42}$$

This case is special. The expression (37) is valid only when the boundary condition in the solution of the task is $r = R$. Expression (36) is the final solution of equation (2) that we want to determine depending on the temperatures.

Thus, the given equation (2) and the initial boundary conditions, related to thermal problems for cylindrical bodies, satisfied the solution of the equation.

Equation (36) allows the temperatures and temperature stresses generated on the contact surfaces of the cutting and rock-destroying tools to be adjusted.

A model sample of a single-cone bit (Figure 1) was selected as an example and, based on the formula (42), calculations were carried out using the MS-EXCEL-2016 software.

As an example, FZ type downhole milling with an outer diameter of 135 mm, milled tubing object with a diameter of 73 mm with D grade strength group were calculated. The determinant C_d is found by the formula:

$$C_d = \frac{A'_{a_1}}{A_{a_1}}\frac{S_1}{S'_1} \tag{43}$$

where:
A_{a_1} – nominal sample size,
A'_{a_1} – nominal physical size,
S_1 – characteristic sample size,
S'_1 – characteristic physical size.

$$S_1 = \frac{A_{\sigma_1}}{V_1} \tag{44}$$

where:
A_{σ_1} – heat-releasing surface,
$V_1 = A_{a_1} \cdot b_1$ – heat absorbing volume,
$b_1 = 1.73\sqrt{(a_1 \cdot t)}$ – effective heat penetration thickness,
a_1 – thermal diffusivity,
t – milling time.

$$A'\alpha_1 = \pi r^2 - \pi r_1^2 - 3\pi r_2^2 \tag{45}$$

$$A'\sigma_1 = 2\pi r_1 h_1 \tag{46}$$

$$S'_1 = 1060\,\mathrm{m}^{-1} \tag{47}$$

where:
$r = 0.017$ m – outer radius of the bit,
$r_1 = 0.007$ m – inner radius of flush holes,
$r_2 = 0.0015$ m – radius of flush holes,
$h = 0.04$ m – reinforcement height,
$a = 1 \cdot 10^{-5}$ m²/s – temperature-conductivity,
$t = 180$ sec. – time of rock destruction.

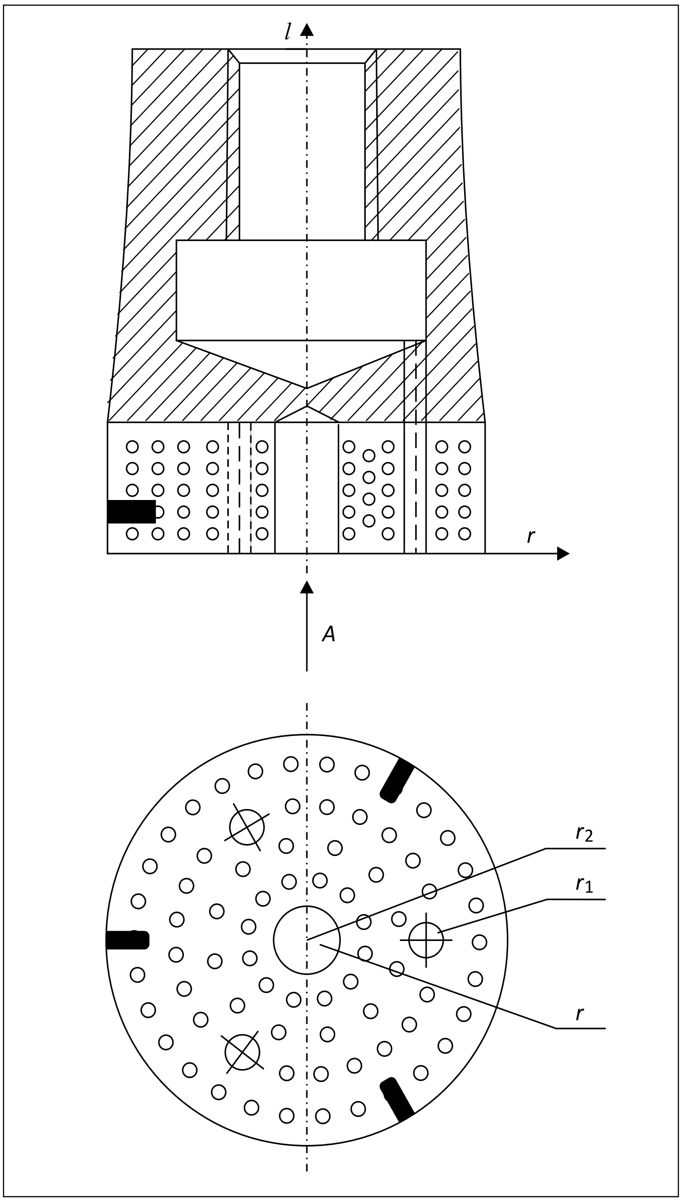

Figure 1. Model sample of a single-cone bit
Rysunek 1. Modelowa próbka świdra jednogryzowego

From the obtained result, graphical dependences of temperature on the radius of the overlap and the time of the rock destruction were built (Figure 2 and 3). Depending on the overlap radius, the temperature changes according to the parabola law. Depending on the time – the temperature first increases, then switches to a stationary mode (in about 55–60 seconds).

Conclusions

3. Mathematical writing of thermal issues has been determined considering thermal stress, heat conduction and heat transfer coefficients affecting temperatures in the tribonodes and contact areas of the cutting tools used in the restoration works in wells.

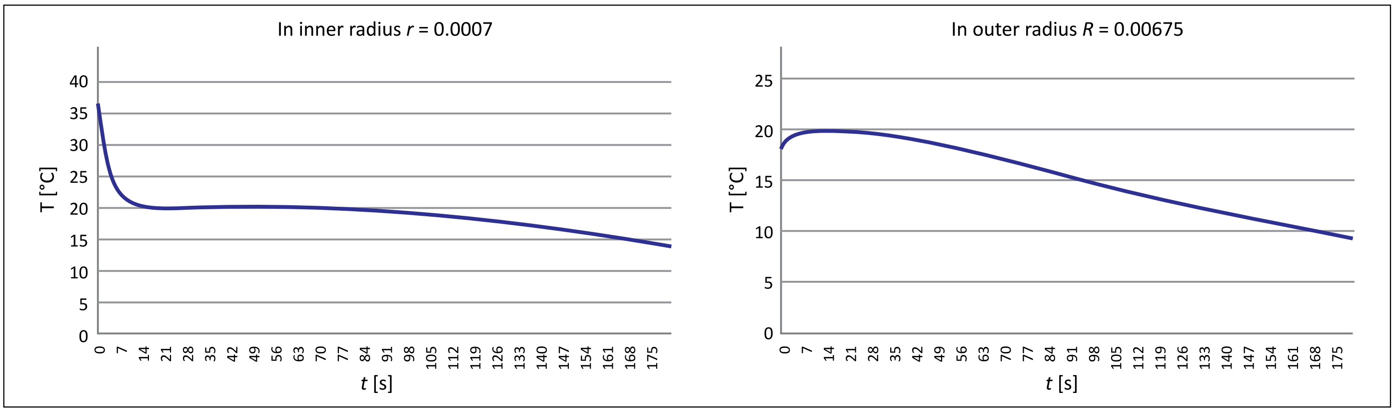

Figure 2. Dependence of the temperature on the cutting bit of the rock destructive tool on the time of rock destruction

Rysunek 2. Zależność temperatury świdra tnącego narzędzia niszczącego skałę od czasu niszczenia

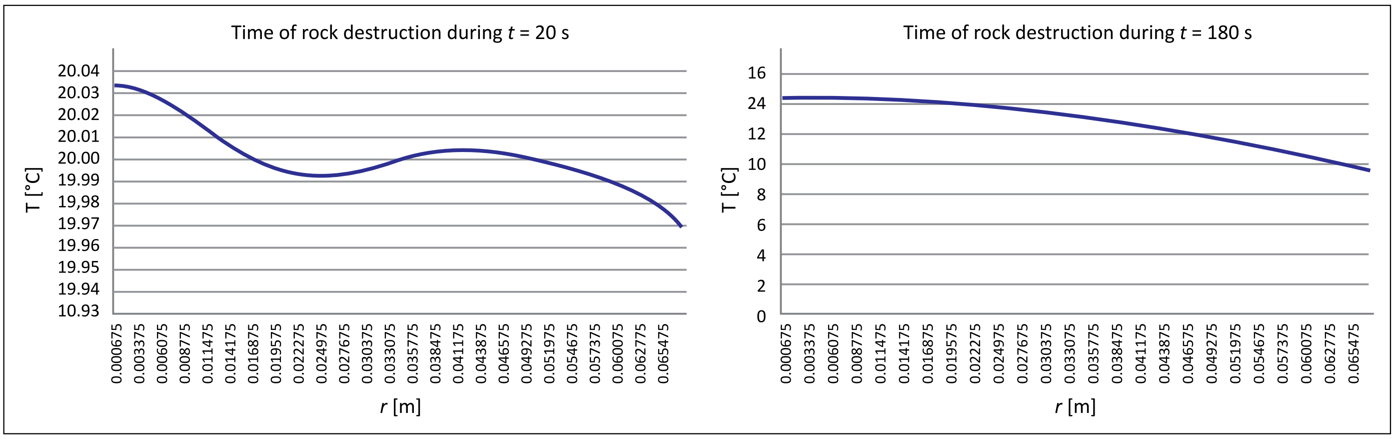

Figure 3. Dependence of temperature on the overlap radius on the cutting bit rock of the rock destructive tool

Rysunek 3. Zależność temperatury od promienia zachodzenia na skałę świdra tnącego narzędzia niszczącego skałę

4. The final solution of the differential equation has been obtained, according to the accepted initial and boundary conditions depending on the radius dimensions of the tool in solving the problems related to heat transfer in the contact areas of the cylindrical cutting equipment and tools.

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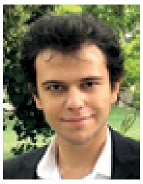

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