Представлені результати чисельних та експериментальних досліджень процесу нагріву алмазних бурових коронок під час буріння свердловин. Розглянуто температурні режими буріння в умовах стаціонарної і нетрадиційної технології імпульсної промивки свердловини. За результатами дослідження теплових процесів на вибою визначено параметри, які забезпечують ресурсо- та енергоефективний режим буріння при імпульсної подачі промивальної рідини

Ключові слова: температурні режими, буріння, CFD моделювання, енергоефективність, імпульсне промивання

Представлены результаты численных и экспериментальных исследований процесса нагрева буровых коронок при бурении скважин. Рассмотрены температурные режимы бурения в условиях стационарной и нетрадиционной импульсной промывки скважины. По результатам исследований тепловых процессов на забое определены параметры, которые обеспечивают энергоэффективный и ресурсосберегающий режим бурения

Ключевые слова: температурне режимы, бурение, CFD моделирование, энергоэффективность, импульсная промывка

UDC 621.7:622.23
DOI: 10.15587/1729-4061.2016.71995

INVESTIGATION OF HEATING OF THE DRILLING BITS AND DEFINITION OF THE ENERGY EFFICIENT DRILLING MODES

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1. Introduction

Well drilling is one of the most energy-intensive technological processes in conducting exploration works. According to many researchers [1], from 85 to 98 % of the energy, supplied to the tool, is used for heat release. The remainder of the energy is spent on residual changes in the tool (1.5–12 %) and the destruction of rocks (0.5–3 %). And if diamond drilling bits are used, 90–95 % of the supplied energy transfers into heat. Thermal conductivity of the tool is 2–3 orders of magnitude larger than the thermal conductivity of rocks and flushing fluids.

Thus, the main amount of heat generated on a working face of borehole, is absorbed by a drilling tool that contributes to its premature wear. High contact temperatures are the main reason that limits the technologies productivity and determines the energy consumption and resource intensity of the drilling process [2]. A critical point of contact temperature, at which the drilling passes into the mode with increased energy consumption and faster tool wear, is the value range around 600 °C.

To improve the efficiency of the process of drilling new wells, new technologies are developed, in particular, drilling with impulse flushing of the working face [3]. This method of flushing allows creating significant gradients in temperatures in the fracture process zone, which contributes to the loss of rock formations strength. The results of the pilot implementation of this technology have demonstrated increasing mechanical velocity of drilling. At the same time, pulse mode of a flushing fluid supply into the well does not always provide efficient cooling of the tool. To prevent overheating of the drilling tool and its premature wear, it is necessary to define the rational parameters of pulse supply of the flushing fluid, which necessitates the research of the heat exchange on the working face of a during drilling.

2. Analysis of scientific literature and the problem statement

Temperature modes of various rock cutting tools have been the subject of studies of a rather large number of theoretical and experimental papers. The absolute majority of researchers considered the drilling process under conditions of continuous flushing of the well. But the approaches to simulations vary, depending on the type of tool and drilling conditions.

Theoretical approaches to simulations of the processes of heating of PDC bits (poly diamond crystalline bits) were proposed in papers [4, 5], and experimental and numerical studies of the processes of heating the elements of PDC bits are carried out in works [6, 7]. The obtained results revealed the patterns of thermal wear of working indenters and identified the ways to optimize the technology of the tool. It is noted that an important factor that determines the cooling performance of drilling tools in the process of well deepening is the velocity field of a flushing liquid flow on the working face. The paper [8] reports a study of a flushing fluid flow on the working face with diamond bit drilling by the methods of computer simulation of hydrodynamics (Computer Fluid Dynamics – CFD simulation).

However, the models used for study thermophysical processes during drilling uses PDC bits are not applicable to determine other types of rock cutting tools, as a result of construction and technological differences. During exploration drilling, the main type of rock cutting tool is a diamond or a hard-alloy drilling bit. Theoretical analysis of the influence of a temperature factor on the efficiency of drilling by diamond drilling bits is presented in the paper [9]. The available papers on this subject were analyzed in the specified work, as well as analytical ratios for calculating the contact temperature with consideration of the design features of the tool and mode parameters of the technological process. At the same time, to obtain a detailed picture of the physical processes on the working face of a well, it is advisable to use mathematical models based on the system of differential equations of convective heat exchange and numerical methods of solution.

CFD simulation of fluid dynamics processes during the flow passing around the drilling bits is carried out in the paper [10], while the papers [11, 12] present calculations of the thermal and mechanical fields in a bit's matrix, which are derived by numerical calculation. At the same time, calculations [9–12] are limited by the case of stationary flushing and may not be used to study impulse well flushing.

One-dimensional mathematical model of non-stationary processes of heating and cooling of the diamond drill bits was developed in the paper [13]. Based on the results of numerical experiments, the dependencies of a contact temperature on the temporal characteristics of impulse flushing were built. The flushing fluid supply intervals and the duration of pauses in the supply were used as temporal characteristics. However, the specified model is built within a one-dimensional approximation and requires further substantiation of the adequacy to physical processes. In addition, the results presented in [13], were obtained only for specific values of downhole power and flushing fluid consumption.

Thus, the problem of temperature modes of diamond drill bits during drilling is not studied sufficiently. In particular, the heating process of drilling bits considering peculiarities of fluid mechanics of the flushing fluid on the working face, and under conditions of the impulse supply of the flushing fluid. Development of drilling technology with impulse flushing of a well requires carrying out of research of this kind to determine technological parameters that provide resource- and energy-efficient mode of diamond drilling.

3. The purpose and objectives of the study

The purpose of this work is a study of convective heat exchange on the working face of a well during drilling by diamond bits and determination of parameters of pulse flushing, enabling energy-efficient and resource-saving drilling modes.

To achieve the goal, the following tasks are to be solved:

– to design a mathematical simulation of fluid mechanics processes on the working face during a well drilling, methods and experimental studies of temperature modes of diamond drill bits with stationary flushing were developed;

– to verify mathematical model by comparing estimated and experimental data, to substantiate the validity of numerical simulation;

– to investigate the effects of pulse flushing on the temperature mode of drilling and determine rational parameters of flushing fluid supply.

4. Materials and methods of research

4. 1. Mathematical model of the processes of convective heat exchange on the working face

A drilling bit consists of a body and a hard alloy matrix. The working end of the matrix is reinforced with diamonds or hard alloy inserts. The matrix is divided into sectors by flushing channels. The number of flushing channels and their dimensions can be different for different bits. In the process of drilling, a flushing fluid (technical water or drill mud), required for cooling the tool and removal of small rock particles (sludge), generated as a result of its destruction, is pumped into the well.

For the simulation of fluid dynamics processes during drilling, a serial drilling bit 01A3 of diameter 76 mm and with 4 flushing channels was considered, Fig. 1. 3D model for the research of the process of flowing around a drilling bit on the working face is presented in Fig. 2. While conducting studies, we adopted technical water as a flushing fluid, pumped into the well in straight flushing scheme. According to the scheme, a flushing liquid is supplied on the working face by a drill pipe handling string. Near working face, passing through the cavity formed between the inner surfaces of the bit and surface of the core, the liquid gets into the well through the bit's flushing channels.

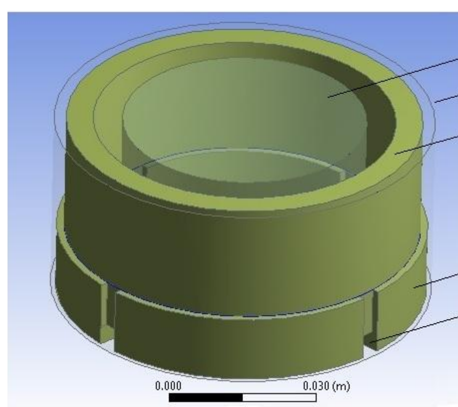

Fig. 1. General view of a diamond drilling bit: 1 — core; 2 — wall of a well; 3 — drilling bit body; 4 — matrix; 5 — flushing channel

We adopted several assumptions when building the simulation. In the first approximation we neglect: the presence of slime in ascending flow; fluid losses due to its absorption by the porous medium of rocks; roughness of the well's walls and core; surface roughness of the working face. We accept that the physical characteristics of a flushing fluid and its temperature are constant values; during the time until the flow is of stable character, the bit delves into rock insignificantly. The amount of fluid under the working end of the matrix is negligibly low, because the main stream moves along the flushing channels. The last assumption is justified, taking into account the relatively small gap between the surface of the rock and the matrix (about 0.3 mm), its substantial hydraulic resistance, the presence of sludge and high temperatures under the end of the matrix, facilitating evaporation of a liquid. Given the minor dimensions of pore-destructive indenters – drilling diamonds compared to the size of the matrix, and their high thermal conductivity, we assume that the effect of the geometry of the diamonds is negligible.

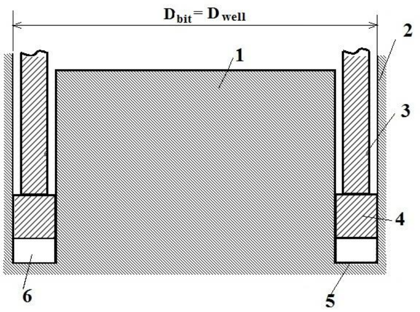

Fig. 2. 3D model of the estimated area: 1 — core; 2 — wall of a well; 3 — drilling bit body; 4 — matrix; 5 — surface of a working face; 6 — flushing channel

For a description of the fluid dynamic processes we will use the standard two-parameter $k-\varepsilon$ turbulence model [14]. Mathematical model includes a system of differential equations of momentum transfer for a flushing fluid, continuity and transfer of characteristics of turbulence, heat transfer in the matrix and the bit's body.

$$\frac{\partial u_j}{\partial x_j}=0, \tag{1}$$

$$\frac{\partial u_i}{\partial \tau}+\frac{\partial}{\partial x_j}\left(u_j u_i\right)=-\frac{1}{\rho}\frac{\partial p}{\partial x_i}+\frac{\partial}{\partial x_j}\left(\left(\nu+\nu_t\right)\frac{\partial u_i}{\partial x_j}\right), \tag{2}$$

$$\frac{\partial k}{\partial \tau}+\frac{\partial}{\partial x_j}\left(u_j k\right)=\frac{\partial}{\partial x_j}\left(\left(\nu+\frac{\nu_t}{\sigma_k}\right)\frac{\partial u_i}{\partial x_j}\right)+$$
$$+\frac{\nu_t}{\rho}\left[\frac{\partial u_i}{\partial x_j}-\frac{\partial u_j}{\partial x_i}\right]\frac{\partial u_i}{\partial x_j}-\varepsilon, \tag{3}$$

$$\frac{\partial \varepsilon}{\partial \tau}+\frac{\partial}{\partial x_j}\left(u_j \varepsilon\right)=\frac{\partial}{\partial x_j}\left(\left(\nu+\frac{\nu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right)+$$
$$+C_{1\varepsilon}\frac{\varepsilon}{k}\nu_t\left[\frac{\partial u_i}{\partial x_j}-\frac{\partial u_j}{\partial x_i}\right]\frac{\partial u_i}{\partial x_j}-C_{2\varepsilon}\frac{\varepsilon^2}{k}, \tag{4}$$

$$c_m\rho_m\frac{\partial t_m}{\partial \tau}=\frac{\partial}{\partial x_j}\left(\lambda_m\frac{\partial t_m}{\partial x_j}\right), \tag{5}$$

$$c_b\rho_b\frac{\partial t_b}{\partial \tau}=\frac{\partial}{\partial x_j}\left(\lambda_b\frac{\partial t_b}{\partial x_j}\right), \tag{6}$$

where $i=1, 2, 3$ correspond to x, y, z – coordinates in Cartesian system; u are averaged components of velocity vector; k is the turbulence kinetic energy; ε is the energy dissipation of turbulence; p is the average pressure in a flow; ν is the coefficient of kinematic viscosity of a flushing fluid; ν_t is the coefficient of kinematic viscosity of turbulence; ρ is the density of a flushing fluid; τ is the time; $C_{1\varepsilon}=1.44$, $C_{2\varepsilon}=1.92$, $\sigma_k=1.0$, $\sigma_\varepsilon=1.3$ are the empirical constants of turbulence model; λ_m, λ_b, c_m, c_b, ρ_m, ρ_b are thermal conductivity, heat capacity and density of the matrix and the body of the bit, respectively; t_m, t_b are temperatures of the matrix and bit's body, respectively.

To solve the equations (1)–(6), the following expression for turbulent viscosity is used

$$\nu_t=C_\mu\frac{k^2}{\varepsilon}, \tag{7}$$

where the value of the constant $C_\mu=0.09$. In the initial time $\tau=0^-$ the bit is motionless and is washed by the flushing fluid flow with a source temperature. In the moment $\tau=0^+$, the drilling process starts with the rotation of the bit. Boundary conditions for (1), (2) are as follows.

In the output section we set "soft" boundary conditions

$$u_1=u_2=0,\quad \frac{\partial u_3}{\partial x_3}=0.$$

On all the surfaces of the contact of a rock with a fluid we set conditions of adhesion

$$u_1=u_2=u_3=0.$$

Fluid velocity equal to the rotation velocity of the bit on the surface of the drilling bit. In the input section, we set the flushing fluid consumption. For the case of continuous flushing

$$Q(\tau)=Q_0,$$

where Q_0 is the specified flushing fluid consumption.

In the case of impulse flushing, the fluid is supplied with duration $\delta\tau_1$ and the pauses in supply $\delta\tau_2$. The consumption is a time function

$$Q(\tau)=\begin{cases} Q_o\sin\left(\frac{2\pi\tau^*}{\delta\tau_1}\right), & \tau\in\left(\delta\tau_1\right), \\ 0, & \tau\in\left(\delta\tau_2\right), \end{cases}$$

where τ^* is the time from the start of supply.

For equations (5) and (6), on all surfaces of the bit in contact with the flushing fluid, we set the condition of convective heat exchange. Heat exchange coefficient α was determined using hydrodynamic solution of the task and the equation [15]

$$\alpha=0.021\cdot\left(\frac{w\cdot D}{\nu}\right)^{0.8}\cdot Pr^{43}\cdot\left(\frac{Pr}{Pr_c}\right)^{0.25}\cdot\frac{\lambda}{D},$$

where w is the flow rate, determined by the solution of hydrodynamic task of type $w=\sqrt{u_1^2+u_2^2+u_3^2}$; D is the hydraulic diameter of the corresponding part, λ is the thermal conductivity of fluid; $Pr=\frac{\nu}{a}$ is the Prandtl criterion; a is the coefficient of temperature conductivity of fluid; Pr_c is the Prandtl criterion, calculated by thermal physical characteristics that are taken at a bit's temperature.

For the characteristics of turbulence, the method of wall functions applies. At the working end of the matrix we set a heat flow

$$-\lambda_m \frac{\partial t_m}{\partial x_3}\bigg|_F = k_p q,$$

where k_p is the coefficient of heat flow distribution on the working face between a tool and rock [13]; q is the heat flow of the friction generated on the working face; F is the surface area of the matrix.

4. 2. Experimental studies of the process of heating drilling bits

Experimental bench research of temperature settings on the working face during drilling was carried out on the base of the Department of Mineral Prospecting Technology at the National Mining University (Dnipropetrovsk, Ukraine). General view of experimental bench is presented in Fig. 3. For registration and control of drilling parameters we applied: flowmeter – to measure fluid flow consumption, to measure the axial load, to measure the power at the terminals of the electric motor of the drilling rig H-348, manometer for pressure control of the flushing fluid. Mechanical drilling velocity was recorded by recorder CK-5.

Fig. 3. General view of experimental bench: 1 – drilling machine ZIF–650M; 2 – lead pipe; 3 – drilling tools; 4 – laptop PC; 5 – charger for modules WAD-AIK-BUS (USB); 6 – analog-digital converter WAD-AIK-BUS (USB); 7 – granite block

The experiments were conducted with both serial diamond drilling bits 01A3 diameter 76 mm and thermo-mechanical models of bits TMBS. The bits models were bit rings of diameter 73 mm with welded matrix of steel with 4 flushing channels.

Definition of temperature fields during drilling was conducted using thermocouples of K type, installed in the granite block with its preparation on the track of the well (Fig. 4) as well as the measuring-computing complex (Fig. 3), which consists of the WAD-AIK-BUS (USB) modules produced by "Akon", designed for measuring of electric values, information processing and its transfer to the main computational network (computer) through a 2-wire serial interface RS-485 or USB.

Fig. 4. Block of rock with thermocouples

Detailed methodology of conducting pilot studies was described in [16]. When drilling with diamond bits, the value of contact temperature was taken in the moment of cutting the thermocouple by the bit. When using the models of bits, direct destruction of rock did not apply. Friction heat generated during the rotation of the model on the surface of the working face, without deepening. A thermocouple was put in the rock at a distance of approximately 1 mm deep from the surface of the working face.

5. The results of the research of fluid dynamics and thermal processes during drilling and their discussion

Fig. 5, 6 present the results of numerical simulation of hydrodynamic and thermal fields during drilling with continuous flushing, corresponding to the mode parameters: down-hole power N=6 kW, flushing fluid consumption Q=60 L/min.

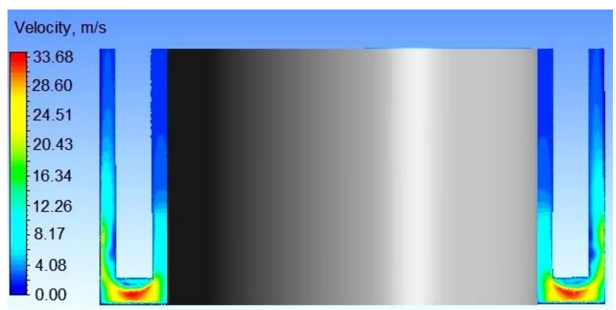

Fig. 5. The results of calculation of velocity field on the working face during drilling

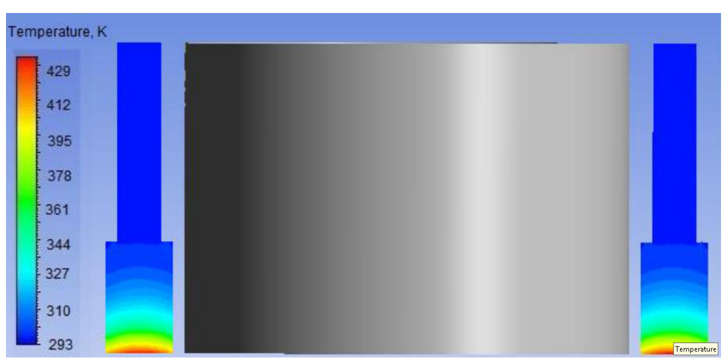

Fig. 6. The results of calculation of temperature field on the working face during drilling

As follows from Fig. 5, the flow in flushing channels speeds up by almost 4 times, thereby providing intensive convective heat removal. Velocity distribution along the surface of the bit allowed to determine heat exchange coefficients and calculate temperature field in the body of the bit, Fig. 6. Temperature field is shown for the section corresponding to the middle sector of the bit's matrix. The obtained results show a slight temperature drop along the width of the matrix and the body. As the distance from the surface of the working face increases, the bit's temperature quickly drops approaching the flushing fluid flow temperature.

Comparison of experimental and calculated data on the temperature of diamond bits is in Table 1.

Table 1

The calculated and experimental values of the contact temperature

Bit type	Mode parameters		t_{exp}	t_{culc}
	N, kW	Q, L/min		
TMKC-4-5-5	2.1	15	177	203
TMKC-4-10-2	2.1	15	232	256
01A3	6.3	60	200	173
01A3	6.3	10	470	424

The divergence of calculated and experimental data is on average 12 %, which is quite satisfactory. Thus, we can talk about the adequacy of the proposed mathematical model for the study of thermal and hydrodynamic processes on the working face when drilling by diamond bits.

A mathematical simulation was used to study the thermal mode of a drilling bit with impulse flushing. From the technological point of view, one must choose those durations of time intervals of pauses and supply, with which the bit's temperature does not exceed 600 °C, at which diamonds and matrix start losing their abrasive properties [1]. As shown in [13], contact temperature depends on many parameters, among which the most significant are: down-hole power, flushing fluid consumption and pulse mode intervals. Thus, the task of determining the temperature mode is multiparameter, the solution to which is easy to present in the form of nomograms with appropriate parameters. To build a nomogram, a series of computational experiments was performed using the above-presented simulation. In the course of calculations, parameters of flushing $\delta\tau_1$ and $\delta\tau_2$ were set and maximal valid values of the level of down-hole power and flushing fluid consumption were defined. By using the interpolation of calculation results, a nomogram was built to determine drilling mode parameters for different time intervals of pauses and supply $\delta\tau_1$ and pauses in the supply $\delta\tau_2$, which is presented in Fig. 7.

The data obtained by calculations allow choosing the modes, which provide resource and energy efficiency when organizing drilling with impulse flushing. As an example of using the chart, let us consider symmetric impulse flushing at $\delta\tau_1 = \delta\tau_2 = 3$ s. In accordance with the data in Fig. 6, one can determine that minimal valid flushing fluid consumption must not be less than 15 L/min, at down-hole power not larger than 6.8 kW. The realization of these conditions will keep normal drilling mode temperature during chosen intervals of pulse and pause in the supply of flushing fluid. Similarly it is possible within specified mode parameters: flushing fluid consumption and down-hole power to define valid parameters of pulse supply.

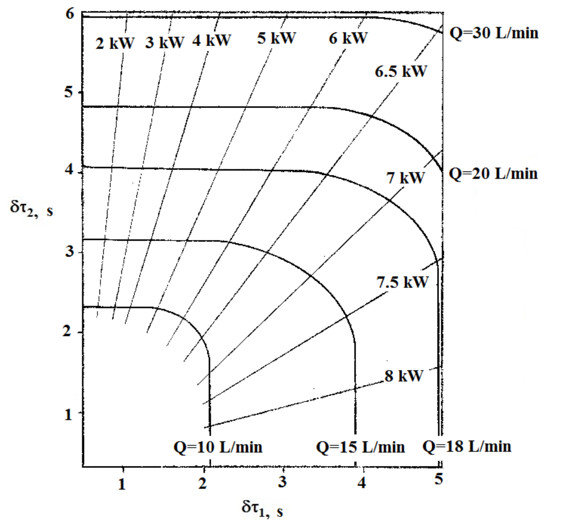

Fig. 7. Nomogram for determining parameters of pulse $\delta\tau_1$ and $\delta\tau_2$ depending on the flushing fluid consumption Q and down-hole power

6. Conclusions

1. The mathematical model of integrated hydrodynamic and heat processes on the working face during well drilling with consideration of a pulse mode of flushing was designed, which is based on the system of differential equations of the turbulent motion of flushing fluid and heat transfer in the body of a drilling bit. The study of such a task is not possible by analytical methods, while experimental methods involve technical difficulties and require considerable financial costs. The proposed model has made it possible to consider the processes of heating and cooling of a drilling bit under conditions of non-stationary convective heat exchange and to take into account the design features of the tool.

2. To assess the validity of the mathematical simulation, the methodology of experimental research of thermal modes of drilling was developed. The bench studies of the heating process of diamond drill bits were carried out. A conducted comparative analysis of the calculated and experimental data indicates that the divergence of the experimental and calculated data on contact temperature averages not larger than 12 %. Thus, the reliability of the results of numerical simulation was presented that allows recommending the proposed model for the study of convective heat exchange on the working face during a well drilling.

3. A parametric study of the impact of impulse flushing on a temperature mode of drilling was conducted, on the results of which we built a nomogram for determining the parameters of a pulse supply that provide energy-efficient and resource-saving drilling mode. The resulting nomogram is an user-friendly tool for the evaluation of drilling parameters without performing complex calculations, which allows, by selected settings of pulse flushing, defining mode parameters, valid in terms of efficient temperature drilling mode: flushing fluid consumption, down-hole power.

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