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MODELLING OF DEEP WELLS THERMAL MODES

A. Bulat[1], B. Blyuss[1], A. Dreus[2], B. Liu[3], S. Dziuba[1*]

[1]*Institute of Geotechnical Mechanics named by N. Poljakov of National Academy of Sciences of Ukraine, Dnipro, Ukraine*
[2]*Oles Honchar Dnipro National University, Dnipro, Ukraine*
[3]*Jilin University, Changchun, China*
**Corresponding author: e-mail sergejdzuba@gmail.com, tel. +380672575044, fax: +380567134540*

ABSTRACT

Purpose. Investigation of various heat-exchange conditions influence of the tower liquid on the deep wells thermal conditions.

Methods. Methods of heat-exchange processes mathematical modeling are used. On the basis of the developed scheme for calculation, the thermal condition in a vertical well with a concentric arrangement of the drill-string was investigated. It was assumed that the walls of the well are properly insulated, and there is no flow or loss of fluid. The temperature distribution in the Newtonian (water) and non-Newtonian (clay mud) liquid along the borehole was simulated taking into account changes in the temperature regime of rocks with depth. To verify the calculation method and determine the reliability of the results, a comparative analysis of the calculated and experimental data to determine the temperature of the drilling liquid in the well was performed.

Findings. A mathematical model for the study of temperature fields along the well depth was proposed and verified. A steady-state temperature distribution along the borehole is obtained for various types (Newtonian or non-Newtonian) tower liquid, with a linear law of change in rocks temperature with depth. It has been established that the temperature of the liquid flow at the face of hole and at the exit to the surface depends on the type of liquid used and the flow regime. It has been established that due to thermal insulation of drill pipe columns, heat-exchange between the downward and upward flow is reduced, which leads to a decrease in the temperature of the downward flow at the face of hole, providing a more favorable temperature at the face, which contributes to better destruction of the rock and cooling the tool during drilling.

Originality. The nature of temperature distribution and changes along the borehole under the steady-state mode of heat-exchange in a turbulent and structural flow regime for both Newtonian and non-Newtonian circulating liquid are revealed.

Practical implications. The proposed mathematical model and obtained results can be used to conduct estimates of the thermal conditions of wells and the development of recommendations for controlling the intensity of heat-exchange processes in the well, in accordance with the requirements of a specific technology.

Keywords: *heat-exchange processes in wells, mathematical modeling, tower flow, geothermic gradient, Newtonian and non-Newtonian liquid*

1. INTRODUCTION

Heat-exchange processes are the main factors determining the effectiveness of the main technological processes related to the exploration and development of mineral deposits, the operation of underground infrastructure projects, the technologies development for the use of renewable energy sources, etc.

In particular, heat-exchange between the drilling fluids and rock is taken into account during deep-drilling in the development of coal deposits, as well as oil and gas. It is known (Makovei, 1986) that providing the necessary head and rate specification of pumping appliance that supports the circulation of drilling fluid in the well, makes up to 80% of the total drilling process energy cost. Water-base drilling fluid retains technological properties up to 230 – 250°C. Under the action of high temperatures, due to the presence of a geothermal gradient, the geological and technological characteristics of the drilling fluid change, which must be taken into account when determining the required energy consumption (Hasan & Kabir, 2010). At higher temperatures, it is necessary to switch to the oil base of the fluid and apply more complex mixtures. Traditional approaches to drilling do not allow drilling deep wells at high temperatures for a long time, since the heat resistance of existing drilling equipment does not exceed 300°C. At temperatures above 150°C, there are significant problems with instrumentation, especially with electronics.

Therefore, when designing drilling technology, special attention is paid to factors affecting the efficiency of the well flushing process, both during exploratory drilling (Kozhevnykov & Dreus, 2018) and in production wells during oil production (Cazarez-Candia & Vásquez-Cruz, 2005).

The thermal condition of a well largely determines the efficiency of gas hydrate development technologies (Bondarenko & Sai, 2018), technologies for well equipment with some types of gravel filters (Kozhevnykov, Sudakov, Dreus, & Lysenko, 2013) and well insulation (Sudakov, Dreus, Ratov, & Delikesheva, 2018), for controlling thermal conditions in underground bodies design and operation (Falshtynskyi, Dychkovskyi, Lozynskyi, & Saik, 2012; Lozynskyi et al., 2018). Heat-exchange processes play the key role in the development of geothermal resources (Toth & Bobok, 2015; Morozov, 2017) and other alternative energy technologies, in which the well performs the function of a heat exchanger (Sarbu & Sebarchievici, 2014; Wight & Bennett, 2015).

Thus, the design and creation of steady-state deep wells, their effective operation is not possible without studying the thermal conditions in the wells, which requires the development of appropriate models and methods for calculating the processes of drilling fluids heating in the wells.

2. A SHORT PROFILE OF THE STATE OF THE ART

In the second half of the 20th century, active work on drilling deep wells began throughout the world. The experience of such works has shown that it is impossible to limit oneself to the consideration of hydrodynamic processes in wells without taking heat-exchange into account (Es'man & Gabuzov, 1991). One of the first bulky fundamental studies of thermal conditions in wells are monographs (Bulatov, 1971; Pudovkin, Chugunov, & Salamatin, 1977), where various factors affecting the temperature of heat conductor in the well are analyzed, mathematical models are developed and analytical solutions are obtained for various problems of convective heat-exchange in wells. Due to the complexity of conducting experimental studies in operating wells, it is mathematical modeling that is the main tool for studying heat-exchange in the corresponding technologies.

To date, there are a sufficient number of works devoted to the study of heat-exchange processes in wells. So, for example, in the works (Fomin, Hashida, Chugunov, & Kuznetsov, 2005; Li et al., 2016; Zhang et al., 2018) mathematical models are presented and semi-analytical solutions are obtained for determining the thermal interaction between the flow of the tower liquid and the rock massif. Changes in liquid temperature along the borehole may affect the stability of the well walls. The effect of heat-exchange on the stress state of the well walls is considered in (Wu et al., 2017). The mathematical model and calculation method for determining the temperature distribution along the borehole of production wells of complex structures are presented in works (Yang, Li, Deng, Meng, & Li, 2015; Sui, Horpestad, & Wiktorski, 2018), computer modeling of hydrodynamic and thermal processes in the located near a face well was performed in works (Gorman, Abraham, & Sparrow, 2014; Dreus & Lysenko, 2016).

Analysis of the known works shows that the heating of motive fluids is affected with many factors: the magnitude of the geothermal gradient and the depth of the well; heat flow generated with pumps and drilling tools operation; heat from electrical cables; the heat of cement hydration used to isolate wells, etc. Among these factors, the most significant is the temperature of the rocks surrounding the well. It is known that the temperature of rocks increases with depth in accordance with the value of the geothermal gradient, which is largely determined by specific geological conditions (Zhou, Xiong, & Tian, 2015; Sevillano, De Andrade, & Sangesland, 2017). Most models used in practice assume a linear dependence of the rock temperature distribution on depth. However, the actual law of temperature distribution in wells may deviate from the linear, and with a well depth of more than 2 km, often there are no data, both on geothermal gradient value, and on rock temperature. Table 1 shows the known data (Dreus, Kozhevnikov, & Chayka, 2007) on the rocks temperature in some deep and geothermal wells, which indicate the ambiguity of the temperature distribution of rocks in depth.

Table 1. Rock temperature in some deep and geothermal wells (Dreus, Kozhevnikov, & Chayka, 2007)

Well	Region	Depth, m	Bottom hole temperature, °C
Bertha-Rogers	Oklahoma, USA	9583	260
Montgomery	Texas, United States	7132	244
Athlete-1 (geothermal)	Southern California, USA	1440	357
River Reni (geothermal)	Southern California, USA	2469	371
Kola	Kola Peninsula, Russia	12261	212
Pauzhetska (geothermal)	Kamchatka, Russia	600	195
Great Bath Sources (geothermal)	Kamchatka, Russia	425	174
Tyrnauz (geothermal)	North Caucasus, Russia	4001	223
Saatli	Azerbaijan	8324	148
Kryvyi Rih	Kryvyi Rih, Ukraine	5382	85
CTB-Oberpfaltz	Bavaria, Germany	9901	300

Thus, the design of drilling technologies or the exploitation of deep wells often requires variable calculations. The type of flushing fluid affects the heating of the stream circulating in the well. As it is well known, depending on the purpose of the well, environmental conditions and the type of rock, various types of drilling liquids can be used (Luo, Xu, & Jiang, 2014; Alimonti & Soldo, 2016; Bulat et al., 2016). Consequently, the efficiency of heating liquids depends on both their thermophysical properties and the conditions of heat-exchange with the rock.

The purpose of this work is a theoretical study of various tower liquid heat-exchange conditions influence on the thermal conditions of deep wells.

3. MATHEMATICAL STATEMENT OF PROBLEM

Consider the thermal condition in a vertical well with a concentric arrangement of the drill-string. Suppose that the well walls are properly insulated, therefore, both the inflow and fluid loss are absent. The diagram of the fluid circulating in the well is shown in Figure 1.

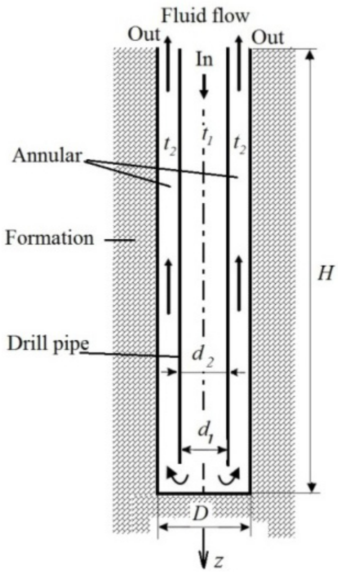

Figure 1. Scheme to the calculation of the thermal condition in the well

Based on the heat balance condition, the system of differential equations describing the steady-state temperature distribution of the fluid flow along the borehole is:

$$Gc_p \frac{dt_1}{dz} = k_l \pi (t_2 - t_1) + \frac{\sum_i Q_{1i}}{H}; \quad (1)$$

$$Gc_p \frac{dt_2}{dz} = k_l \pi (t_2 - t_1) - \alpha_w \pi D (t_2 - t_w) + \frac{\sum_j Q_{2j}}{H}, \quad (2)$$

where:

G – mass flow rate;

c_p – liquid heat capacity;

t_1 – downward flow temperature;

t_2 – upward stream temperature;

t_w – well wall temperature, which is a function of the current depth;

k_l – heat-transfer coefficient through the drill-string between the downward and upward flow;

α_w – heat exchange coefficient on the well wall;

H – well depth;

Q_{1i}, Q_{2j} – heat sources in the downward and upward flows, respectively.

The heat-transfer coefficient k_l is determined from the expression:

$$k_l = \left(\frac{1}{\alpha_1 d_1} + \frac{1}{2\lambda_l} \ln \frac{d_2}{d_1} + \frac{1}{\alpha_2 d_2} \right)^{-1}, \quad (3)$$

where:

d_1 – internal diameter of the drill-string;

d_2 – external diameter of the drill-string;

λ_1 – thermal conductivity coefficient of the drill-string pipes;

α_1 – heat exchange coefficient on the inner surface of the drill-string;

α_2 – heat exchange coefficient on the outer surface of the drill-string.

System (1) – (2) is supplemented with initial conditions:

$$\text{at } h = 0, \qquad t_1 = t_{in}; \quad (4)$$

$$\text{at } h = H, \qquad t_2 = t_1 + \Delta t, \quad (5)$$

where:

$t_1 = t_{in}$ – the temperature of the downward flow on the surface;

$t_2 = \Delta t$ – the bottom-hole temperature increment, due to the operation of the drilling tool in the processes of drilling wells.

Important parameters affecting heat-exchange between the tower liquid and the surrounding rock are heat-exchange coefficients. As it is known, these coefficients are not physical properties and depend on the type of fluid, flow regime, surface state, etc. To determine such coefficients, semi-empirical criterion equations are used in practice. In papers (Santoyo, Garcia, Espinosa, Santoyo-Gutiérrez, & González-Partida, 2003), the analysis of such expressions used to calculate convective heat-exchange in wells during the flow of Newtonian and non-Newtonian liquids is performed. Table 2 presents the basic equations for determining heat-exchange coefficients in wells in drilling technologies.

It should be noted that with prolonged circulation of the flushing fluid in the well, the temperature distribution on the walls of the well will differ from the natural temperature of the rock. In general case, it is necessary to solve both the problem of temperature distribution in the fluid and the surrounding rock massif (Fomin, Hashida, Chugunov, & Kuznetsov, 2005; Wu, Zhang, & Jeffrey, 2014). In engineering calculations, to take into account the history of non-stationary heat-exchange between the rock and drilling liquid, it is advisable to apply the concept of non-stationary heat-exchange coefficient (Willhite, 1967):

$$k_\tau = \alpha_w \frac{t_w - t_2}{t_r - t_2}, \quad (6)$$

where:

t_r – the natural temperature of rocks.

Table 2. Criterion equations for calculating heat-exchange coefficients in wells

Drilling fluid	Formula	Flow regime	Source
Water	$\alpha_w = 0.021\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.43}\left(\frac{\mathrm{Pr}}{\mathrm{Pr}_w}\right)^{0.25}\frac{\lambda}{D^*}$	Turbulent	Dzhuraev & Merkulov, 2016
Air**	$\alpha_w = 0.0178\,\mathrm{Re}^{0.8}\frac{\lambda}{D^*}$	Turbulent	Dzhuraev & Merkulov, 2016
Water	$\alpha_w = 4.36\frac{\lambda}{D^*}$	Laminar	Incropera & DeWitt, 1990
Oil solution	$\alpha_w = 0.027\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.33}\left(\frac{\mu}{\mu_w}\right)^{0.14}\frac{\lambda}{D^*}$	Turbulent	Sieder & Tate, 1936
Mud	$\alpha_w = 0.018\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.43}\left(\frac{\mathrm{Pr}}{\mathrm{Pr}_w}\right)^{0.25}\frac{\lambda}{D^*}$	Turbulent	Chernyak & Zolotorenko, 1992
Mud (pipe flow)	$\alpha_w = 2.9\left(Pe\frac{d_1}{H}\right)^{0.35}\mathrm{Re}''^{-0.1}\left(\frac{\mu}{\mu_w}\right)^{0.17}\frac{\lambda}{D^*}$	Structure	Chernyak & Zolotorenko, 1992
Mud (annular flow)	$\alpha_w = 4.7\left(Pe\frac{d_1}{H}\right)^{0.31}\mathrm{Re}''^{-0.1}\left(\frac{\mu}{\mu_w}\right)^{0.17}\frac{\lambda}{D^*}$	Structure	Chernyak & Zolotorenko, 1992

$$\mathrm{Re} = \frac{\rho w D^*}{\mu}; \qquad \mathrm{Re}'' = \frac{\rho w^2}{\tau_0}; \qquad Pe = \frac{wD^*}{a}; \qquad \mathrm{Pr} = \frac{\mu}{\rho a}.$$

ρ – liquid density; w – liquid flow rate; $D^* = D$ – for flow inside the drill- string; $D^* = D - d_2$ – for flow in the annulus of the well; μ – coefficient of dynamic liquid viscosity; τ_0 – shearing stress of a non-Newtonian liquid; a – liquid thermal diffusivity; λ – heat-conduction coefficient of the fluid; the subscript "w" means that the parameter is taken at wall temperature: ** – compressed air can be used when drilling deep wells in permafrost or dry areas.

The definition of this coefficient is a separate complex task. Moreover, a universal analytical expression for this coefficient cannot be obtained. For drilling wells with prolonged circulation of the flow, you can use the approximate formula proposed in (Pudovkin, Chugunov, & Salamatin, 1977):

$$k_\tau = \alpha_w\left(\frac{1}{1+Bi\ln\left(1+\sqrt{2Fo}\right)}\right), \tag{7}$$

where:

$Bi = \frac{\alpha_w D^*}{\lambda_r}$ – Biot criterion;

$Fo = \frac{\alpha_r \tau_c}{D^{*2}}$ – Fourier criterion;

λ_r – heat-conduction of rock;

a_r – heat diffusivity of rock.

After the appropriate transformations, system (1) – (2), (4) – (5) can be reduced to a second-order ordinary differential equation with one unknown function and the corresponding boundary condition:

$$\frac{d^2t_1}{dz^2} - A\frac{dt_1}{dz} - Bt_1 - Ct_w(z) + Q = 0; \tag{8}$$

$$t_1\big|_{z=0} = t_{in}, \left.\frac{dt_1}{dz}\right|_{z=H} = t_{in}, \tag{9}$$

where:

$$A = \frac{k_\tau \pi D}{Gc_p};$$

$$B = \frac{k_\tau \pi^2 D k_l}{\left(Gc_p\right)^2};$$

$$C = B;$$

$$Q = \frac{d}{dz}\left(\frac{1}{Gc_p}\cdot\frac{\sum_i Q_{1i}}{H}\right) + \frac{k_l\pi}{\left(Gc_p\right)^2}\cdot\frac{\sum_j Q_{2j}}{H}.$$

The temperature distribution in the annulus upstream is determined from the expression:

$$t_2 = t_1 + \frac{Gc_p}{k_l\pi}\cdot\frac{dt_1}{dz} - \frac{1}{k_l\pi}\cdot\frac{\sum_i Q_{1i}}{H}. \tag{10}$$

In the particular case, with constant liquid flow rates, constant thermophysical properties and heat power sources, as well as for the linear distribution law, formulae (8) – (9) has an analytical solution. However, in the general case, to solve a differential equation with boundary conditions (8) – (9), it is advisable to use numerical methods.

To verify the calculation method and determine the reliability of the results, a comparative analysis of the calculated and experimental data to determine the temperature of the drilling liquid in the well was performed. As experimental data, we took data (Shcherban' & Chernyak, 1974) obtained during the drilling of deep wells by the Nadvornenskyi management of drilling activities (Ivano-Frankivsk, Ukraine). The temperature mode of the well was studied using a deep autonomous temperature recorder. The experiments were carried out at the well 20, the depth of which was 4069 m. The temperature measurements were carried out at depths of 500, 1000, 2000 m, as well as at the surface. Clay mud was used for flushing the wells. Measurements were performed after 2 – 3 hours of washing, i.e. at steady-state temperature. Characteristics of the liquid: $\rho = 1160$ kg/m^3; $\lambda = 0.71$ W/(m·°C); $c_p = 3.45$ kJ/(kg·°C) averaged thermal and physical characteristics of the rock $\lambda_r = 2.21$ W/(m·°C); $a_r = 0.308 \cdot 10^{-6}$ m^2/s; $\tau_0 = 7.07$ N/m^2. The average depth of the borehole diameter is $D = 0.21$ m; the clay mud rate is $G = 20$ l/s; and the temperature gradient is $\sigma = 0.025$ K/m. The discrepancy of experimental data was estimated with:

$$\delta = \frac{t^{\exp} - t^{calc}}{t^{\exp}} \cdot 100\% . \quad (11)$$

Table 3 shows the results of experimental measurements and calculation of drilling liquid temperature for the given conditions.

Table 3. Comparative analysis of calculated and experimental data

Depth, m	Downstream temperature, °C			Upstream temperature, °C		
	Experiment	Calculation	δ	Experiment	Calculation	δ
0	27	27	—	37	40	7.5%
500	30	28	7%	39	41	5%
1000	32	29	10%	41	42	3%
2000	34	31	9%	43	44	2%

As we can see from the results of the test calculation, the discrepancy between the experimental data and the numerical calculation using the considered model does not exceed 10%, which can be considered entirely satisfactory.

4. CALCULATION RESULTS AND DISCUSSION

On the basis of the mathematical model proposed above, steady-state temperature regimes were investigated in a well with a depth of 2000 m and a diameter of 0.19 m, under various heat-exchange conditions. The inner and outer diameter of the drill pipe is $d_1 = 0.096$ m and $d_2 = 0.1143$ m, respectively, the heat-conduction coefficient of steel drill pipe is $\lambda_t = 34$ W/(m·K), the water flow is $G = 70$ l/min, which provides a turbulent flow regime, and $G = 18$ l/min for clay mud that provides a structural flow regime. The temperature at the entrance to the drill pipe is set to 10°C, in the first approximation we neglect all sources of heat, except for the heat of the surrounding rocks:

$$\sum_i Q_{1i} = \sum_j Q_{2j} = 0 . \quad (12)$$

The value of the geothermal gradient is taken to 0.03 deg/m, which is most often used in practical calculations (Alkhasov, 2017). Note that, in accordance with Table 1, the heat-exchange in the turbulent flow of clay solutions, oil-based solutions and water differs slightly. This effect is explained by the fact that during turbulent flow there is an intensive mixing of the flow, the flow structure of clay or oil solutions is destroyed, and they become close to Newtonian liquids.

Figure 2 shows the temperature in the downward (inside the drill pipe) and upward (in the annular) flows of water and clay mud in the well in the absence of thermal insulation coatings for various liquids.

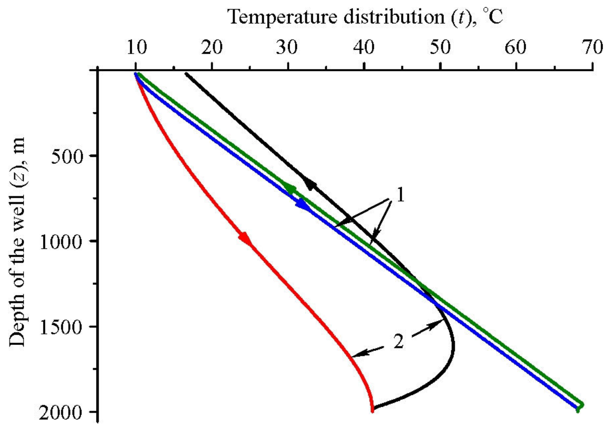

Figure 2. Steady-state temperature distribution (t), over the depth of the well (z) in the water flow (1) and clay mud (2)

Analysis of the results presented in Figure 2 shows that under steady-state conditions, the temperature distribution in the Newtonian liquid flow (water) takes almost linear character, while the temperature difference in the downward and upward flows is insignificant along the entire borehole, due to intense heat-exchange between these streams. In the clay mud, with structural flow, heat-exchange between the rock and the upward flow, as well as between the upward and downward flows is less intense, due to an increase in the convective components of thermal resistance. Thus, the maximum temperature value decreases as compared with the flow of a Newtonian liquid, but the temperature difference between the downward and upward flows increases. On the surface, this difference is about 7°C.

It was theoretically and experimentally shown in (Dreus, Kozhevnikov, Sudakov, & Vakhalin, 2016) that in order to increase the efficiency of well drilling, it is desirable to ensure a low temperature of the downward flow at the face of hole. This is possible by insulating the drill-string pipes and, thus, reducing the intensity of heat-exchange between the downward and upward flows. In Figure 3 shows the results of thermal conditions calculation in wells in the presence of thermal insulation coating on drill pipes, where the equivalent heat-conduction coefficient of drill pipes is $\lambda_t = 0.14$ W/(m·K).

Temperature distribution of water and clay mud flows, presented in Figure 3 shows that due to thermal insulation, heat-exchange between the downward and upward flow is reduced, which leads to a decrease in the temperature of the downward flow at face of hole. Thus, it is possible to provide a more favorable temperature at the bottom, which contributes to a better destruction of the rock and cooling of the tool during drilling. At the same time, it should be remembered that a decrease in the temperature of liquids leads to an increase in its viscosity and, consequently, an increase in the energy costs of its transportation to the face.

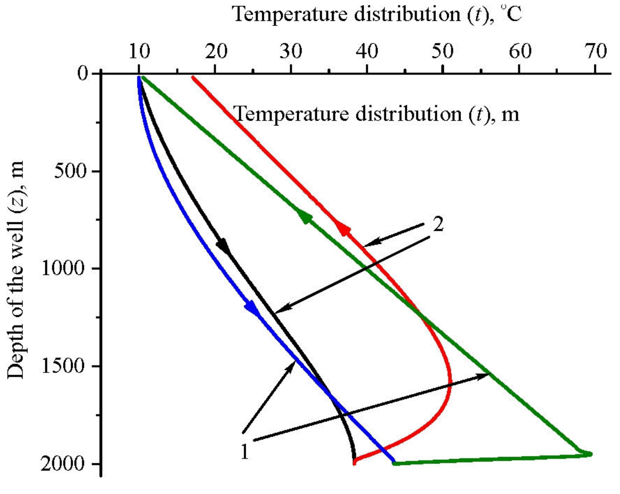

Figure 3. Steady-state temperature distribution (t), over the well depth (z) in the water flow (1) and clay mud (2) during the thermal insulation of drill pipes

It should also be noted that in the technologies of using the heat of the Earth, it is necessary to ensure the highest possible temperature of the upward flow at the outlet, that is, on the surface. The above calculation results show that in this case it is preferable to use non-Newtonian liquids under the structural flow regime. However, if we apply the technologies of borehole walls thermal insulation, for example, thermal insulation of core-shells, as follows from the results obtained above, the use of Newtonian fluids will allow to obtain a higher difference between the downward and upward flow on the surface.

5. CONCLUSIONS

As a result, of thermal condition studies performed using the proposed mathematical model established the following.

In the steady-state heat exchange and turbulent mode of both Newtonian and non-Newtonian tower liquids, the temperature distribution along the borehole is linear, corresponding to the linear law of change in the temperature of rocks, with a slight difference between the downward and upward flows. In the case of the structural flow of non-Newtonian liquids, the maximum temperature decreases, and the difference between the downward and upward flows increases.

Thermal management in wells is possible by creating thermal insulation coatings on drill pipes and/or well walls. Thus, thermal insulation of drill pipes can reduce the temperature of the downward flow and increase the temperature difference between the downward and upward flows.

The simulation results suggest that it is possible to control the temperature of the tower liquids at the face of the well and at the exit to the surface.

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МОДЕЛЮВАННЯ ТЕПЛОВОГО РЕЖИМУ ГЛИБОКИХ СВЕРДЛОВИН

А. Булат, Б. Блюсс, А. Дреус, Б. Лю, С. Дзюба

Мета. Дослідження впливу різних умов теплообміну циркулюючої рідини на тепловий режим глибоких свердловин.

Методика. Використано методи математичного моделювання процесів теплообміну. На основі розробленої схеми до розрахунку досліджувався тепловий режим у вертикальній свердловині з концентричним розташуванням бурильної колони. Передбачалося, що стінки свердловини належним чином ізольовані, приплив і втрати рідини відсутні. Моделювався розподіл температур у потоках ньютонівської (води) та неньютонівської (глинистого розчину) рідин уздовж стовбура свердловини з урахуванням зміни температурного режиму гірських порід з глибиною. Для верифікації методики розрахунку і визначення достовірності результатів був виконаний порівняльний аналіз розрахункових та експериментальних даних з визначення температури промивної рідини у свердловині.

Результати. Запропонована і верифіційована математична модель для дослідження температурних полів з глибиною свердловини. Отримано стаціонарний розподіл температур уздовж стовбура свердловини для різних типів (ньютонівських або неньютонівських) циркулюючих рідин при лінійному законі зміни температури гірських порід з глибиною. Виявлено, що температура потоку рідини на вибої свердловини і на виході на денну поверхню залежить від типу використовуваної рідини і режиму течії. Встановлено, що за рахунок термоізоляції колони бурильних труб знижується теплообмін між низхідним і висхідним потоками, що призводить до зниження температури низхідного потоку на вибої свердловини, забезпечуючи більш сприятливий температурний режим на вибої, який сприяє кращому руйнування породи та охолодженню інструменту при бурінні.

Наукова новизна. Виявлено характер розподілу та зміни температури вздовж стовбура свердловин при стаціонарному режимі теплообміну в турбулентному і структурному режимах течії як для ньютонівських, так і неньютонівських циркулюючих рідин.

Практична значимість. Запропонована математична модель і отримані результати можуть використовуватися для проведення оціночних розрахунків теплових режимів свердловин та розробки рекомендацій з управління інтенсивністю теплообмінних процесів у свердловині відповідно до вимог конкретної технології.

Ключові слова: *процеси теплообміну у свердловинах, математичне моделювання, циркулюючий потік, геотермічний градієнт, ньютонівські та неньютонівські рідини*

МОДЕЛИРОВАНИЕ ТЕПЛОВОГО РЕЖИМА ГЛУБОКИХ СКВАЖИН

А. Булат, Б. Блюсс, А. Дреус, Б. Лю, С. Дзюба

Цель. Исследование влияния различных условий теплообмена циркулирующей жидкости на тепловой режим глубоких скважин.

Методика. Использованы методы математического моделирования процессов теплообмена. На основе разработанной схемы к расчету исследовался тепловой режим в вертикальной скважине с концентрическим расположением бурильной колоны. Предполагалось, что стенки скважины надлежащим образом изолированы, приток и потери жидкости отсутствуют. Моделировалось распределение температур в потоках ньютоновской (воды) и неньютоновской (глинистого раствора) жидкостей вдоль ствола скважины с учетом изменения температурного режима горных пород с глубиной. Для верификации методики расчета и определения достоверности результатов был выполнен сравнительный анализ расчетных и экспериментальных данных по определению температуры промывочной жидкости в скважине.

Результаты. Предложена и верифицирована математическая модель для исследования температурных полей по глубине скважины. Получено стационарное распределение температур вдоль ствола скважины для различных типов (ньютоновских или неньютоновских) циркулирующих жидкостей при линейном законе изменения температуры горных пород с глубиной. Выявлено, что температура потока жидкости на забое скважины и на выходе на дневную поверхность зависит от типа используемой жидкости и режима течения. Установлено, что за счет термоизоляции колоны бурильных труб снижается теплообмен между нисходящим и восходящим потоками, что приводит к снижению температуры нисходящего потока на забое скважины, обеспечивая более благоприятный температурный режим на забое, который способствует лучшему разрушению породы и охлаждению инструмента при бурении.

Научная новизна. Выявлен характер распределения и изменения температуры вдоль ствола скважин при стационарном режиме теплообмена в турбулентном и структурном режимах течения как для ньютоновских, так и неньютоновских циркулирующих жидкостей.

Практическая значимость. Предложенная математическая модель и полученные результаты могут использоваться для проведения оценочных расчетов тепловых режимов скважин и разработки рекомендаций по управлению интенсивностью теплообменных процессов в скважине в соответствии с требованиями конкретной технологии.

Ключевые слова: *процессы теплообмена в скважинах, математическое моделирование, циркулирующий поток, геотермический градиент, ньютоновские и неньютоновские жидкости*

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ABOUT AUTHORS

Anatolii Bulat, Doctor of Technical Sciences, Director of the Institute of Geotechnical Mechanics named by N. Poljakov of National Academy of Sciences of Ukraine, 2a Simferopolska St, 49005, Dnipro, Ukraine. E-mail: office.igtm@nas.gov.ua

Borys Blyuss, Doctor of Technical Sciences, Head of the Department of Geodynamic System and Vibration Technologies, Institute of Geotechnical Mechanics named by N. Poljakov of National Academy of Sciences of Ukraine, 2a Simferopolska St, 49005, Dnipro, Ukraine. E-mail: bblyuss@gmail.com

Andrii Dreus, Doctor of Technical Sciences, Associate Professor of the Fluid Mechanics and Energy and Mass Transfer Department, Oles Honchar Dnipro National University, 72 Haharina Ave., 49010, Dnipro, Ukraine. E-mail: dreus.andrii@gmail.com

Baochang Liu, Doctor of Philosophy, Professor of the Drilling Engineering Department, Jilin University, 938 Ximinzhu St, 130061, Changchun, China. E-mail: liubc@jlu.edu.cn

Serhii Dziuba, Candidate of Technical Sciences, Senior Researcher of the Department of Geodynamic System and Vibration Technologies, Institute of Geotechnical Mechanics named by N. Poljakov of National Academy of Sciences of Ukraine, 2a Simferopolska St, 49005, Dnipro, Ukraine. E-mail: sergejdzuba@gmail.com