Journal of Engineering Physics and Thermophysics, Vol. 79, No. 5, 2006

MATHEMATICAL SIMULATION OF A NONSTATIONARY THERMAL FIELD IN THE "WELL-BEING-DRILLED–ROCKS" SYSTEM

R. A. Valiullin, A. A. Sadretdinov, R. F. Sharafutdinov, and R. B. Bulgakov

UDC 536.622

A mathematical model and results of calculation of a nonstationary thermal field in the process of drilling a well in rocks having different thermophysical properties, with a laminar mode of flow of the drilling mud, are considered. The distributions of temperature over the well bore in different drilling regimes are given. It is shown that when the drilling is stopped, the temperature anomalies in the well are preserved for 24–48 h in the intervals of alive beds.

We will consider the problem of formation of a thermal field during drilling of a well, extraction of drilling tools, and in the process of temperature recovery on termination of drilling. In constructing a mathematical model, the processes of heat transfer by heat conduction in the radial and vertical directions and convective heat transfer, and also the presence of drilling tools and of an absorbing bed are taken into account. Heat release on the drilling bit is neglected.

The equation of heat transfer in the "well-being-drilled–rocks" system in a cylindrical geometry has the form [1]

$$\rho_i c_i \frac{\partial T_i}{\partial t} + \frac{\partial}{\partial z}\left(m\rho_i c_i T_i v\right) = \frac{1}{r}\frac{\partial}{\partial r}\left(r\lambda_i \frac{\partial T_i}{\partial r}\right) + \frac{\partial}{\partial z}\left(\lambda_i \frac{\partial T_i}{\partial z}\right), \tag{1}$$

$$T_i\Big|_{r=R_i-0} = T_{i+1}\Big|_{r=R_i+0}, \quad \lambda_i \frac{\partial T_i}{\partial r}\Big|_{r=R_i-0} = \lambda_{i+1}\frac{\partial T_{i+1}}{\partial r}\Big|_{r=R_i+0}, \quad i = 1, 2, 3 ; \tag{2}$$

$$T_i\Big|_{z=z_{\max}} = T_6\Big|_{z=z_{\max}}, \quad \lambda_i \frac{\partial T_i}{\partial z}\Big|_{z=z_{\max}} = \lambda_6 \frac{\partial T_6}{\partial z}\Big|_{z=z_{\max}}, \quad i = 1, 2, 3, 4, 5 . \tag{3}$$

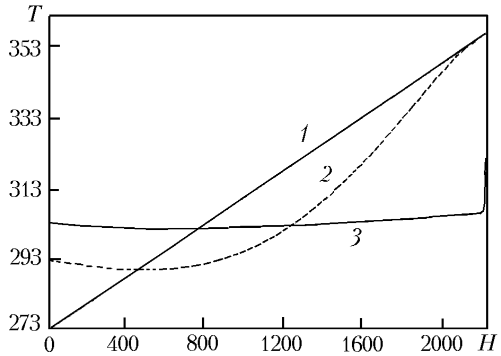
All of the parameters are functions of the coordinates and time. The initial and boundary conditions are as follows:

$$T_i\Big|_{t=0} = T_{\rm g}(z), \; i = 1, 2, 3, 4, 5, 6 ; \quad \frac{\partial T_1}{\partial r}\Big|_{r=0} = 0 , \quad T_4\Big|_{r=R_{\rm th}} = T_{\rm g}(z) ; \quad T_i\Big|_{z=0} = T_0 , \; i = 1, 2, 3, 4 . \tag{4}$$

The radius of thermal effect $R_{\rm th}$ is selected from the condition according to which the temperature perturbation does not reach the right boundary. The influence of the absorbing bed on formation of a thermal field is taken into account by solving the problem of nonisothermal displacement of the bed fluid by the drilling mud in the Backley–Leverett approximation:

$$m\frac{\partial S}{\partial t} + w(t, r)\frac{1}{r}\frac{\partial F(S)}{\partial r} = 0 , \tag{5}$$

Bashkiriya State University, 32 Frunze Str., Ufa, 450074, Russia; email: gframil@rambler.ru. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 79, No. 5, pp. 85–85, September–October, 2006. Original article submitted May 12, 2005.



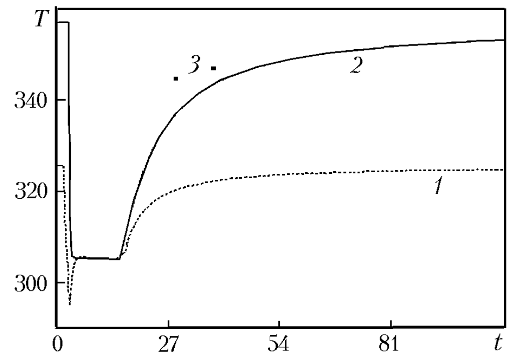


Fig. 1. Temperature distribution over the well depth: 1) geotherm; temperature in the well directly after the bottoming of the drilling tools; 3) same at the time of termination of drilling. T, K; H, m.

Fig. 2. Time dependence of temperature at different depths: 1) H = 1500; 2) 2400 m; 3) field data. T, K; t, h.

$$\rho_b c_b \frac{\partial T}{\partial t} + w(t, r) \frac{1}{r} \frac{\partial}{\partial r} \left[\rho_{fl} c_{fl} TF(S) + \rho_1 c_1 TF(1 - S) \right] = \frac{\partial}{\partial z} \left(\lambda_b \frac{\partial T}{\partial z} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left(r \lambda_b \frac{\partial T}{\partial r} \right). \quad (6)$$

The phase permeabilities are functions of the saturations of the bed fluid and drilling mud. The initial and boundary conditions for Eqs. (5) and (6) have the form

$$S\Big|_{r=R_3} = 1, \quad S\Big|_{t=0} = 0; \quad P\Big|_{r=R_3} = P_w, \quad P\Big|_{r=R_{sup}} = P_{sup}; \quad T\Big|_{r=R_3, z=z_{max}} = T_3(t, z_{max}). \quad (7)$$

Taking into account the fact that the pressure field is established much faster than the temperature field, we assume that the distribution of velocities in the well is known and it obeys the stationary distribution of pressure in the well.

The solution of the system of equations (1)–(7) with initial and boundary conditions is obtained by the method of control volume [2, 3].

Below we present some of the calculated results on formation of a temperature field in the process of drilling and after its termination. The following values of time were used in the calculations: 3 h to lower the drill stem, 13 h on drilling, and 3.5 h to pull the drill stem out. The diameter of the drilling pit was 0.216 m, the inner diameter of the drill stem was 0.11 m, the outer diameter 0.127 m, and the drilling-mud viscosity was $5 \cdot 10^{-3}$ Pa·sec. The temperature of the neutral bed was 0^oC; the geometrical gradient and thermophysical parameters of the rock correspond to those typical of sandstone.

Figure 1 presents the distributions of temperature along the length of the well inside the drill stem after running the tools to the bottom (curve 2) and at the moment of termination of the drilling (curve 3). The sinking of the drilling tools leads mainly to disturbance of the thermal field in the well bore. The surrounding rocks experience the main thermal effect in the process of well drilling. The temperature distribution is influenced by heat exchange with the surrounding rocks and the opposite stream moving outside the drill stem. After a certain interval of time, the temperature of the drilling mud (at the rates of its pumping-in, 10 m^3/sec) that reaches the region of the drill bit becomes practically equal to the initial temperature of the drilling mud coming from above. In the temperature distribution over the depth, one can observe transitions from positive to negative temperature anomalies (the difference between the temperature in the well and the geothermal temperature at the given depth).

Figure 2 presents the results of calculation of the formation of temperature in the well at different depths in the process of drilling and termination of drilling (Fig. 2, curves 1 and 2), as well as the results of the tests carried out in the well (Fig. 2, points 3). The measurements were carried out in the well 9 h and 18 h after termination of the drilling and withdrawal of the drilling tools. The processes of descent of the drilling tools and drilling of the well are accompanied by a decrease in the temperature, whereas the circulation of the drilling mud during drilling leads to equalization of temperature at different depths (Fig. 2, portions where curves 1 and 2 coincide). It is seen that after termination of the drilling the main rate of temperature recovery is observed during the first 24 h; in 48 h the temperature anomaly (relative to the geothermal temperature at the given depth) is equal to 5–10 deg, depending on the depth.

Thus, after termination of drilling the temperature anomalies (5–10 deg) in the well within alive beds are preserved for 24–48 h.

NOTATION

c_i, heat capacity of the ith medium, J/(kg·K); $c_b = mc_1(1 - S) + mc_{fl}S + (1 - m)c_3$; $F(S) = k_1/(k_1 + \mu_0 k_{fl})$, Buckley–Leverett function; H, bed thickness, m; k_{fl} and k_1, phase permeabilities of the bed fluid and drilling mud; m, porosity; P_{sup}, pressure on the supply loop, Pa; P_w, pressure in the well, Pa; Q, volumetric flow rate of the drilling mud pumped into the bed, m^3/sec; R_i, radius of the ith medium, m; R_3, radius of the well, m; R_{sup}, radius of the supply loop, m; R_{th}, radius of thermal effect, m; r, radial coordinate, m; S, saturation of the drilling mud; T, bed temperature, K; T_0, temperature on the Earth's ground, K; $T_g(z)$, geothermal distribution of temperature, K; T_i, temperature of the ith medium, K; t, time, sec; v, velocity of motion of the drilling mud in the well, m/sec; $w(t, r) = Q/(2\pi H)$, m^2/sec; z_{max}, maximum depth of drilling, m; z, vertical coordinate, m; λ_i, thermal conductivity of the ith medium, W/(m^2·K); $\lambda_b = m\lambda_1(1 - S) + m\lambda_{fl}S + (1 - m)\lambda_3$, μ_0 μ_1/μ_{fl}; ρ_i, density of the ith medium, kg/m^3; $\rho_b = m\rho_1(1 - S) + m\rho_{fl}S + (1 - m)\rho_3$. Subscripts: g, geotherm; fl, bed fluid; sup, supply loop; b, bed; w, well; th, thermal effect; i = 1, 2, 3, 4, 5, 6 relate to the drilling mud inside the drilling stem, drilling tools, drilling mud outside the drill stem, rock above the bed, bed, and rock below the bed, respectively; max, maximum drilling depth.

REFERENCES

1. M. G. Alishaev and M. D. Rosenberg, *Nonisothermal Filtration in Development of Oil Fields* [in Russian], Nedra, Moscow (1985).
2. S. Patankar, *Numerical Methods for Solving Problems of Heat Transfer and Dynamics of Fluid* [Russian translation], Énergoatomizdat, Moscow (1984).
3. A. A. Samarskii, *The Theory of Difference Schemes* [in Russian], Nauka, Moscow (1977).