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MATHEMATICAL SIMULATION OF THE AZIMUTHAL-RADIAL DISTRIBUTION OF TEMPERATURE IN A WELL IN THE PRESENCE OF HEAT SOURCES

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The results of theoretical investigations of radial and azimuthal distributions of temperature in a well–rock system in the presence of heat sources are presented. The problem considered is connected with determination of the intervals of fluid motion outside the column by thermal methods. It is shown that in the case of long existence of the channel of fluid overflow outside the column, useful information can be obtained by creating a "contrast" temperature, for example, by heating the fluid inside the casing and subsequently measuring the azimuthal distribution of temperature in the process of its recovery on disconnection of a heater.

The determination of the intervals of fluid motion outside a column is an important problem of well logging [1, 2]. At the present time, various methods are used for its solution, including thermometry. Thermal investigations of wells allow one to determine not only the intervals, but also the channels of fluid motion outside a column. In [3], the problem of formation of a thermal field in the presence of a short-duration thermal perturbation outside a column caused by fluid throttling is considered. However, the long operation of a well accompanied by throttling heating-up of the fluid outside the column leads to equalization of the azimuthal distribution of temperature, which complicated the solution of the problem of revealing the channel for fluid overflow. In this case, to increase the informativeness of thermal investigations, the well–bed system is brought out of the state of thermal equilibrium by creating a "contrast" temperature inside the well by heating the fluid inside it.

We will consider the following problem. In the cased well, let there be an overflow channel assigned by the azimuthal angle φ_0. Throttling heating-up of the fluid is observed in the overflow channel. At a certain instant of time, a heater is turned on in the well, and the fluid in the well is heated up. Thereafter, the heater is turned off, and the azimuthal and radial distributions of temperature in the well are investigated.

In the mathematical statement of the problem, the following assumptions have been made: convective heat transfer in the vertical direction is neglected, which makes it possible to reduce the problem to conductive heat transfer in the plane of the transverse section of the well (system of coordinates r, φ); it is assumed that in each cross section (for each fixed value of the coordinate z) the fluid temperature in the overflow channel remains constant, and the dependence on the coordinate z is not considered. On putting the well in operation, an overflow outside the column appears, and it is assumed that the temperature of the throttling fluid in the overflow channel increases linearly during a certain interval of time up to a certain value T_{ov} and thereafter remains constant. At a certain instant of time the heater is turned on. It is assumed that the heating of the fluid in the column to a certain value T_h occurs instantaneously, i.e., natural heat convection is neglected.

The geometry of the problem takes into account the presence of the casing, cement collar, and the rock around the well. The position of the overflow channel is assigned by the radius R_{ch} and azimuthal angle φ_0 (Fig. 1).

The mathematical statement of the problem with allowance for symmetry relative to the azimuthal angle ($0 \le \varphi \le \pi$) which divides the overflow in two has the following form [3, 4]:

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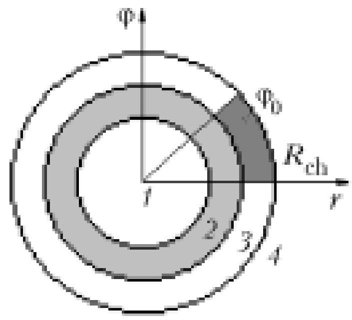

Fig. 1. Geometry of the problem: 1) space inside the channel; 2) iron casing; 3) cement collar; 4) rock.

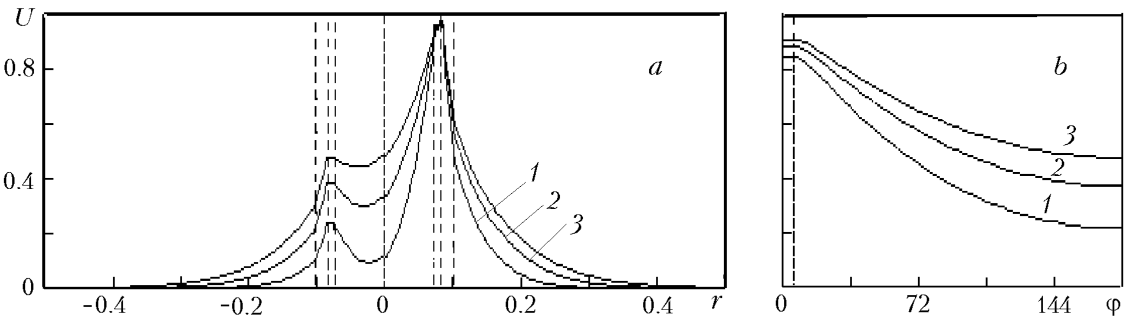

Fig. 2. Time dependence of radial (a) and azimuthal (b) temperature distributions in the absence of a heat source inside the casing: 1) 120; 2) 240; 3) 360 min; φ_0 = 12°; vertical dashed lines, boundaries of the media and overflow half-angles.

$$c_i \rho_i \frac{\partial U_i}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left(\lambda_i \frac{\partial U_i}{\partial r} \right) + \frac{\lambda_i}{r^2} \frac{\partial^2 U_i}{\partial \varphi^2} .$$

At the boundaries of the media

$$U \Big|_{r=R_i-0} = U \Big|_{r=R_i+0} , \quad \lambda_i \frac{\partial U}{\partial r} \Big|_{r=R_i-0} = \lambda_{i+1} \frac{\partial U}{\partial r} \Big|_{r=R_i+0} , \quad i = 1, 2, 3 .$$

The initial and boundary conditions are

$$U \Big|_{t=0} = 0 , \quad 0 < r < R_4 , \quad 0 < \varphi < \pi ; \quad U \Big|_{r=R_k, 0<\varphi<\pi} = U_{\text{ov}} (t) , \quad t > 0 ;$$

$$U = \begin{cases} 0 , & t < t_{\text{h}} , \ 0 \le r \le R_1 , \ 0 \le \varphi \le \pi , \\ U_{\text{h}} , & t \ge t_{\text{h}} , \ 0 \le r \le R_1 , \ 0 \le \varphi \le \pi ; \end{cases} \quad \frac{\partial U}{\partial \varphi} \Big|_{0 \le \varphi \le \pi, 0 \le r \le R_4} = 0 , \ t > 0 , \quad \frac{\partial U}{\partial r} \Big|_{r=R_4, 0 \le \varphi \le \pi} = 0 , \ t > 0 .$$

The problem is formulated for the dimensionless relative temperature:

$$U = \frac{T (r, \varphi, t) - T_0 (r, \varphi, 0)}{T_{\text{ov}} - T_0 (r, \varphi, 0)} \ \text{ for } \ T_{\text{ov}} > T_{\text{h}} \ \text{ and } \ U = \frac{T (r, \varphi, t) - T_0 (r, \varphi, 0)}{T_{\text{h}} - T_0 (r, \varphi, 0)} \ \text{ for } \ T_{\text{ov}} < T_{\text{h}} .$$

The problem was solved numerically on the basis of the finite-difference method. The multivariant calculations performed have shown that in the presence of a steel column the rate of heating-up of the region inside the well

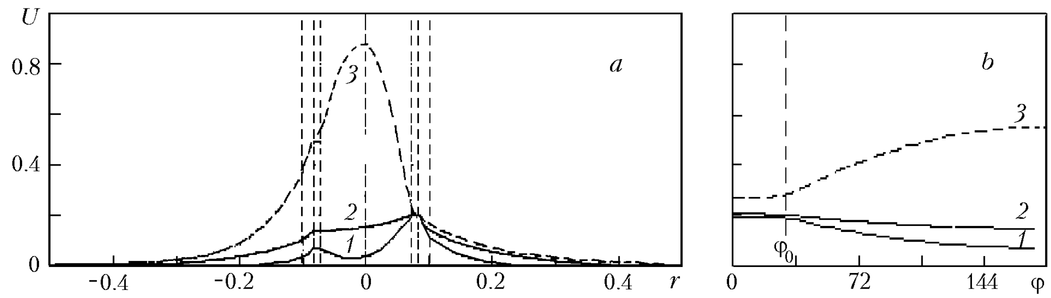

Fig. 3. Time dependence of the radial (a) and azimuthal (b) temperature distributions in the presence of a heat source inside the casing: 1) 120; 2) 600 min; 3) 120 min after turning-off of the heat source; $\varphi_0 = 60^o$; vertical dashed lines, boundaries of the media and overflow half-angles.

is increased (Fig. 2). At the initial instants of time, appreciable radial gradients are observed in the temperature distribution (Fig. 2a). In the azimuthal distribution of temperature (Fig. 2b), maximum heating-up is observed in the region of the overflow channel; with time the heating-up is equalized, mainly due to the effect exerted by the steel casing.

Of greatest interest is the case of a well that has operated for a long time, i.e., when the overflow has existed for an appreciable length of time. The radial and azimuthal distributions of temperature virtually equalize here (Fig. 3, curve 2), which complicates the solution of the problem of determining the location of the overflow channel.

The heating of the fluid in the casing bore disturbs thermal equilibrium (Fig. 3). An analysis of the temperature behavior in the radial section (especially at the points adjoining the overflow sector and at a considerable distance from it) allows the following remarks. The greatest changes in temperature (in the temperature readings before the turning-on of the heater and after) are observed on the axis of the well and at the point farthest from the overflow. At the same time, in the region adjacent to the overflow, during a very small interval of time, the fluid temperature acquires its initial value (that which it was before the turning-on of the heater), equal to the overflow temperature.

On disconnection of the source inside the casing, the temperature field is recovered in both radial (Fig. 3a, curve 3) and azimuthal (Fig. 3b, curve 3) distributions. Azimuthal measurements of temperature around the perimeter of the casing allow one to estimate the angular dimension of the overflow channel. Investigations have shown that it is possible to determine the overflow channel both when $T_{ov} > T_h$ and $T_{ov} < T_h$. The time interval in the course of which one can estimate the size of the overflow channel is limited by the period of fluid heating in the well hole from 30 min to 1 h.

Thus, in the case of long existence of a throttling fluid in the channel outside the column and of the associated heating-up, the azimuthal distribution of the temperature is equalized due to the thermal diffusivity of the media. In this case, useful information on the channel of motion outside the column can be obtained by creating a "contrast" temperature inside the well by heating the fluid inside the casing. With the heater being turned-off, most informative are the measurements made during the first two hours.

NOTATION

c_i, heat capacity of the ith medium, J/(kg·K); R_i, radius of the ith medium, m; R_1 and R_2, R_3 and R_4, inner and outer radii of the column, radii of the well and of the external boundary, respectively, m; R_{ch}, radius of the overflow channel, m; r, radial coordinate, m; $T(r, \varphi, t)$, running temperature, K; $T_0(r, \varphi, 0)$, initial distribution of temperature, K; T_{ov}, maximum temperature of the overflow channel, K; T_h, maximum temperature of the fluid in the column due to heater operation, K; t_h, time of turning-on of the heater, sec; t, time, sec; U, dimensionless temperature; U_i, dimensionless temperature of the ith medium; U_h, dimensionless temperature of the heater; z, vertical coordinate; φ, angular coordinate; ρ_i, densities of media, kg/m^3; λ_i, thermal conductivities of media, W/(m^2·K); φ_0, overflow angle. Subscripts: i, number of the medium; ch, overflow channel; ov, overflow; h, heater.

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