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TEMPERATURE DISTRIBUTION IN ZONE SURROUNDING WELL HOLE BOTTOM

DURING THERMOCHEMICAL TREATMENT

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The temperature distribution in the hole bottom zone of a formation during thermochemical treatment is analyzed, taking into account the heat losses through the formation roof and floor. The characteristic parameters of the temperature propagation zones are determined.

Thermochemical methods for acting upon formations are most effective for removing heavy hydrocarbon components from the hole bottom zone and increasing the inflow of crude (particularly high-viscosity crude) to wells [1-6].

The thermochemical treatment that will be considered here involves the exothermal reaction of magnesium with an acid and is carried out by two technological methods: conduct of the reaction in a special chamber at the hole bottom and directly in the formation itself. The first technique entails round-trip operations and possible damage to the lower portion of the string as a result of extensive acid corrosion and is therefore ineffective in comparison with the methods proposed in [7, 8]. These papers described experimental studies of intra-formation thermochemical treatment that resulted in transport of the heat source directly into the formation. A solution of starch-based powdered or granulated magnesium was pumped into the formation, followed by a hydrochloric acid solution.

When magnesium mixes with an acid in the percolation zone of a formation, there is an exothermal reaction that liberates a large amount of heat (approximately 4200 kcal of heat is released in the combustion of 1 kg of magnesium, and the temperature is raised to 200-250°C, depending on the magnesium concentration), and the surrounding material is heated. This removes waxes, asphalts, and tars from the hole bottom zone and substantially improves formation conductivity (laboratory studies have shown that permeability increases by a factor of 1.5-2.0 after thermochemical treatment), which leads to a rise in well production rate.

It is necessary to establish the extent of the heat propagation zone in order to correctly implement the process and determine the effectiveness with which productive formations can be acted upon and developed. For this purpose, the present paper considers the temperature distribution in the formation zone adjoining the hole bottom during different characteristic periods after the start of heat treatment, taking into account the heat losses through the roof and floor of the productive formation, and considers determination of the effective radius of the temperature propagation zone.

The temperature distribution in a formation is described for the case of a moving combustion front by the solution of the following system of differential equations [8, 9]:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\,\frac{\partial U_0}{\partial r}\right)+\frac{\partial^2 U_0}{\partial z^2}+f\,(r,\,z,\,t)=\frac{1}{a_0^2}\,\frac{\partial U_0}{\partial t},$$

$$\frac{1}{r}\frac{\partial r}{\partial r}\left(r\,\frac{\partial U_1}{\partial r}\right)+\frac{\partial^2 U_1}{\partial z^2}=\frac{1}{a_1^2}\,\frac{\partial U_1}{\partial t},\;\;t>0. \tag{1}$$

Since the temperature fields are symmetric relative to the $z = 0$ plane, we will consider the temperature distribution on this plane. The problem is solved with the following initial and boundary conditions:

$$\tag{2}$$

$$U_0\,(r,\,z,\,t)=U_1\,(r,\,z,\,t)\;\text{when}\;t=0,$$

$$\frac{\partial U_0\,(r,\,z,\,t)}{\partial r}=0\;\text{when}\;z=0, \tag{3}$$

$$U_0\,(r,\,z,\,t)=U_1\,(r,\,z,\,t);\;\lambda_0\,\frac{\partial U_0}{\partial z}=\lambda_1\,\frac{\partial U_1}{\partial z}\;\text{when}\;z=\frac{h}{2}, \tag{4}$$

$$U_1\,(r,\,z,\,t)=0\;\text{when}\;|z|\to\infty, \tag{5}$$

$$\frac{\partial U_0\,(r,\,z,\,t)}{\partial z}=0\;\text{when}\;r=r_0, \tag{6}$$

$$U_0\,(r,\,z,\,t)=U_1\,(r,\,z,\,t)\;\text{when}\;r\to\infty\,. \tag{7}$$

Solution of problem (1)-(7) requires that one know the function f(r, z, t) in the first equation of system (1). It is usually specified in the form of a generalized function for simplicity. Precisely this sort of form was utilized in solving a similar problem in [9, 10].

We will set about solving the problem in a somewhat different manner, by eliminating the singularity in the first equation of system (1) and replacing the influence of the function f(r, z, t) with a separate condition on the heat liberation front:

$$U_0^{(0)}=\frac{q}{(2\sqrt{\pi a_0^2 t})^3}\,\exp\left(-\frac{r^2-r_0^2+z^2}{4a_0^2 t}\right)I_0\left(\frac{rr_0}{2a_0^2 t}\right)\left(0\leqslant z\leqslant\frac{h}{2}\right). \tag{8}$$

After making the substitutions $U_0 = U_0^{(0)} + V_0$, $U_1 = V_1$ we solve the system of equations (1) for f(r, z, t) = 0.

Hankel transformation [11] for the variable reduces this system to the form:

$$\frac{\partial^2 \overline{V}_i}{\partial z^2}-\rho^2\overline{V}_i=\frac{1}{a_i^2}\frac{\partial \overline{V}_i}{\partial t}\;(i=0,1). \tag{9}$$

The Hankel transform of the function $U_0^{(0)}$ after replacement of z by $z - z_0$ has the form:
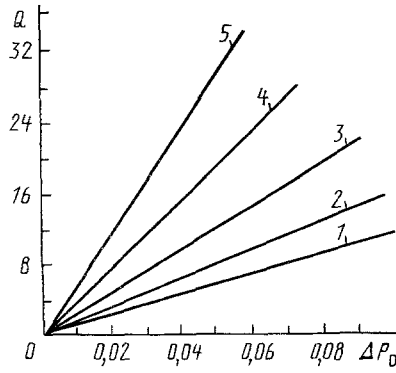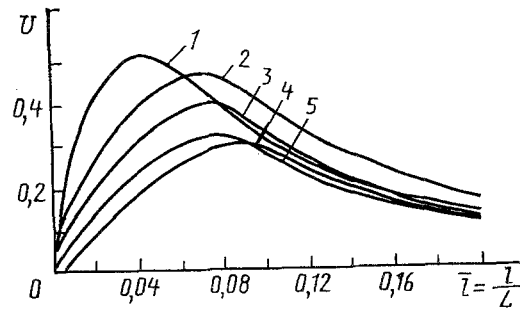
Fig. 1   Fig. 2

Fig. 1. Delivery rate for 2% solution Q (cm^3/sec) as a function of pressure differential ΔP_0 (MPa) at different temperatures. 1) T = 20; 2) 30; 3) 40; 4) 50; 5) 60°C.

Fig. 2. Change in relative temperature U in linear model with exothermal reaction. 1) F = 0.075; 2) 0.144; 3) 0.220; 4) 0.290; 5) 0.362.

$$\overline{U}_0^{(0)} = \frac{q}{4\pi \sqrt{\pi a_0^2 t}} \exp\left(-\frac{|z-z_0|^2}{4a_0^2 t} - a_0^2 t\rho^2\right) J_0(r_0\rho). \tag{10}$$

We carry out Laplace transformation [11] for t and thus reduces Eq. (9) to an ordinary differential equation with the following solutions:

$$\overline{\overline{V}}_0 = A \exp(-g_0 z) + B \exp(g_0 z), \quad \overline{\overline{V}}_1 = C \exp(-g_1 z), \tag{11}$$

where

$$g_i = \sqrt{\rho^2 + \frac{s}{a_i^2}}.$$

Utilizing the inversion formula in [11] for the Hankel transform gives us

$$LU_0 = \int_0^\infty \left[\frac{q}{2\pi a_0^2} \frac{J_0(r_0\rho)}{g_0} \exp(-|z-z_0|g_0) + A \exp(-g_0 z) + B \exp(g_0 z)\right] J_0(r\rho)\,\rho d\rho, \tag{12}$$

$$LU_1 = \int_0^\infty C \exp(-g_1 z) J_0(r\rho)\,\rho d\rho, \tag{13}$$

for the Laplace transforms of the temperature distribution functions.

Conditions (2)-(4) obviously remain unchanged for the Laplace transforms of these functions. Condition (4) was already utilized in determining $\overline{V}$. We employ conditions (2)-(3) in (12)-(13) to obtain a system of linear algebraic equations in A, B, and C. Solution of the resultant system determines these coefficients, and Eqs. (12)-(13) then take the form:

$$LU_0 = \frac{q}{2\pi a_0^2} \int_0^\infty \left[\exp(-|z-z_0|g_0) + \frac{\lambda_0 g_0 \operatorname{ch} g_0(h_1-z_0) + \lambda_1 g_1 \operatorname{sh} g_0(h_1-z_0)}{\lambda_0 g_0 \operatorname{sh} g_0 h_1 + \lambda_1 g_1 \operatorname{ch} g_0 h_1} \times\right.$$

$$\times \exp(-g_0 z)\right] + \frac{(\lambda_0 g_0 - \lambda_1 g_1) \operatorname{ch} g_0 z_0}{\lambda_0 g_0 \operatorname{sh} g_0 h_1 + \lambda_1 g_1 \operatorname{ch} g_0 h_1} \times$$

$$\times \exp(-|h-z|g_0) \frac{J_0(r_0\rho)}{g_0} J_0(r\rho)\,\rho d\rho, \tag{14}$$

$$LU_1 = \frac{q}{2\pi a_0^2} \int_0^\infty \frac{2\lambda_0 g_0 \operatorname{ch} gz}{\lambda_0 g_0 \operatorname{sh} g_0 h_1 + \lambda_1 g_1 \operatorname{ch} g_0 h_1} \times$$

$$\times \exp(-|z-h_1|g_1) \frac{J_0(r_0\rho)}{g_0} J_0(r\rho)\,\rho d\rho. \tag{15}$$

Switching directly back to the originals in Eqs. (14)-(15) leads to complex expressions, and we will therefore not discuss this topic but will consider special cases instead.

Since $g_0 = g_1$ when $a_0 = a_1$, Eqs. (14)-(15) are materially simplified and it is easy to switch to the original. The original of the function in (14) then acquires the following simple form:

$$U_0 = \frac{q}{(2\sqrt{\pi a_0^2 t})^3} \exp\left(-\frac{r^2 + r_0^2}{4a_0^2 t}\right) I_0\left(\frac{rr_0}{2a_0^2 t}\right) \times$$

$$\times \sum_{n=-\infty}^{\infty} \sigma^{|n|} \left\{ \exp\left[-\frac{(nh + z - z_0)^2}{4a_0^2 t}\right] + \exp\left[\frac{(nh + z - z_0)^2}{4a_0^2 t}\right]\right\}, \tag{16}$$

where

$$\sigma = \frac{\lambda_0 - \lambda_1}{\lambda_0 + \lambda_1}.$$

As was noted above, Eq. (10) and hence Eq. (16) were written for the case in which the heat source lies on the plane $z - z_0$. The heat source occupies the entire thickness of the formation in our problem. We therefore integrate over z from $z = 0$ to $z = h_1 = h/2$ and obtain:

$$U^* = \frac{q}{4\pi a_0^2 t} \exp\left(-\frac{r^2 + r_0^2}{4a_0^2 t}\right) I_0\left(\frac{rr_0}{2a_0^2 t}\right) \times$$

$$\times \sum_{n=-\infty}^{\infty} \sigma^{|n|} \left(\text{erf}\, \frac{nh + h_1 - z}{2\sqrt{a_0^2 t}} + \text{erf}\, \frac{nh + h_1 + z}{2\sqrt{a_0^2 t}}\right). \tag{17}$$

The heat source is moving at a specified velocity; its power varies as a function of r_0 and hence of time.

If we assume $r_0^2 = r_w^2 + kt$ and $q = q(t)$ and integrate over time in (17) by superposition and by changing the variable of integration, we obtain the final expression

$$U(r, z, t) = \int_0^t \frac{q(t-\tau)}{4a_0^2 \pi t} \exp\left(-\frac{r_0^2 + r^2 + k(t-\tau)}{4a_0^2 \tau}\right) \times I_0\left(\frac{r\sqrt{r_0^2 + k(t-\tau)}}{2a_0^2 \tau}\right) \left[\text{erf}\, \frac{h-z}{2\sqrt{a_0^2 \tau}} + \text{erf}\, \frac{h+z}{2\sqrt{a_0^2 \tau}} + \right.$$

$$\left. + \sum_{n=1}^{\infty} \sigma^{|n|} \left(\text{erf}\, \frac{nh + h_1 - z}{2\sqrt{a_0^2 \tau}} - \text{erf}\, \frac{nh - h_1 + z}{2\sqrt{a_0^2 \tau}} + \text{erf}\, \frac{nh + h_1 + z}{2\sqrt{a_0^2 \tau}} - \text{erf}\, \frac{nh - h_1 - z}{2\sqrt{a_0^2 \tau}}\right)\right] d\tau \tag{18}$$

Assuming $q = \text{const}$ and $\lambda_0 = \lambda_1$ ($a_0^2 = a_1^2$ in Eq. (18) gives us the corresponding formula from [12].

The series in Eq. (18) converges very rapidly, especially for short times. Making calculations with Eq. (18) consequently presents no difficulties for specified q(t) and k.

We will now consider the specific case in which the magnesium concentration distribution over r is specified. Finding the distribution of magnesium and other heat-liberating materials is one of the main problems. Despite the fact that there have been a few studies on this topic, the question remains unresolved. The most reliable concentration determination method is that based on heat evolution capacity.

Experiments conducted with a linear model have shown that the temperature and magnesium concentration are linearly dependent (Fig. 1) and that the heat-liberating reaction takes place almost instantaneously.

Preliminary calculations made with (18) for the short times indicated above shows that the thermal front lags the heat source and the leakage into the environment is negligible. It is therefore best from the practical standpoint to study the temperature distribution
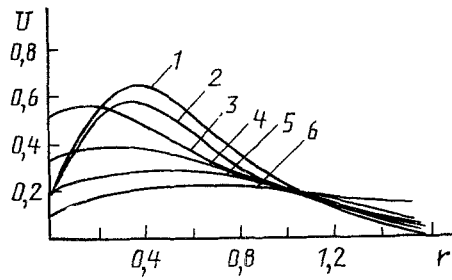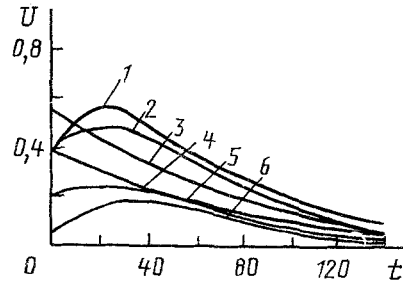
Fig. 3. Relative temperature U as a function of distance r (m): 1) t = 0; 2) 1; 3) 10; 4) 50; 5) 100; 6) 200 h.

Fig. 4. Change in relative temperature as a function of time f h): ∕ 1) r = 0; 2) 0.2; 3) 0.4; 4) 0.6; 5) 0.8; 6) 1.0.

after the reaction terminates. This requires that we know the initial temperature distribution. However, the original temperature distribution around the well (at the conclusion of the reaction) is unknown. We only have the temperature distribution curves for the magnesium concentrations in the starch solution from the linear model at the conclusion of the reaction (see Fig. 2). These curves are also taken as the baseline for the radial temperature distribution, where the problem is more simply solved, e.g., by the incomplete concentrated capacity procedure. The differential equations for the temperature distribution have the following form here [9, 11]:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial U_0}{\partial r}\right) + \alpha\frac{\partial U_0}{\partial z} = \frac{1}{a_0^2}\frac{\partial U_0}{\partial t},\ z = \frac{h}{2},$$

$$\frac{\partial^2 U_1}{\partial z^2} = \frac{1}{a_1^2}\frac{\partial U_1}{\partial t},\ 0 < z < \infty,\ \alpha = \frac{2\lambda_1}{\lambda_0 h}. \tag{19}$$

The condition near the well bottom (3) can be taken with sufficient accuracy to be:

$$\frac{\partial U_0(r,\ z,\ t)}{\partial r} = 0\ \text{as}\ r \to 0, \tag{20}$$

and conditions (7) remain in force. The initial condition is assumed to be:

$$U_0(r,\ z,\ t) = \Phi(r)\ \text{when}\ t = 0,\ z = 0. \tag{21}$$

We solve problem (19)-(21) by first moving the coordinate origin to the z = h/2 plane on the coordinate system adopted. The solution of the problem yielded by the procedure in question on the z = 0 plane in the Laplace transform can be written as [6, 8]:

$$LU = \frac{\beta^2(S)}{S}\left[I_0(\beta z)\int_r^\infty \Phi(\xi)\xi K_0(\beta\xi)\,d\xi + K_0(\beta r)\int_0^r \Phi(\xi)\xi I_0(\beta\xi)\,d\xi\right], \tag{22}$$

where

$$\beta^2(S) = \frac{S}{a_0^2} + \alpha\sqrt{\frac{S}{a_1^2}}.$$

Switching to the original in (22) and utilizing the conventional rules of operational calculus give us

$$U(r, 0, t) = \frac{\alpha}{\sqrt{\pi a_1^2 t}} \int_0^1 \exp\left(-\frac{x}{4(1-x)}\left(\frac{\alpha a_0^2}{a_1}\right)^2 t\right)\left[1 + \right.$$

$$\left. + \frac{x}{2(1-x)}\right]\frac{dx}{2\alpha\sqrt{1-x}} \int_0^\infty \Phi(\xi)\,\xi\exp\left(-\frac{r^2+\xi^2}{4a_0^2 xt}\right) I_0\left(\frac{r\xi}{2a_0^2 xt}\right) d\xi. \tag{23}$$

The calculations require that we establish the analytic form of the function $\Phi(r)$ or specify its tabulated values.

The temperature distribution curves (Fig. 2) can be represented in the form $r^\beta\exp(-\alpha r^2)$ (α, $\beta > 0$). However, U = 0 with this sort of initial temperature distribution near the well bottom ($r \to 0$), which is impossible. In order to avoid this and expand the integral over ξ in Eq. (23), we represent the initial temperature distribution as the function

$$\Phi(r) = B_1\exp(-b_1 r^2) - B_2\exp(-b_2 r^2). \tag{24}$$

Substitution of the expression for $\Phi(r)$ from (24) into (23) and appropriate transformations give us

$$U = \frac{a_0}{a_1}\frac{\alpha}{\sqrt{\pi}}\sqrt{a_0^2 t}\sum_{i=1}^2 (-1)^{i+1} B_i \int_0^1 \left[\frac{1}{\sqrt{1-x}} + \frac{x}{2\sqrt{(1-x)^3}}\right] \times$$

$$\times \exp\left[\left(-\frac{\alpha a_0^2}{2a_1}\right)^2\frac{xt}{1-x}\right]\exp\left(-\frac{b_i r^2}{1+4b_i a_0^2 xt}\right)\frac{dx}{1+4b_i a_0^2 xt}. \tag{25}$$

It is best to reduce the latter integral to the following form for the calculations:

$$U(r, 0, t) = \frac{1}{\sqrt{\pi}}\int_0^\infty x^{-\frac{1}{2}}\exp(-x)[B_1 f_1(r, t, x) - B_2 f_2(r, t, x)]\,dx, \tag{26}$$

where

$$f(x) = \frac{1}{1+4b_i a_0^2 ty(x)}\exp\left(-\frac{b_i r^2}{1+4b_i a_0^2 ty(x)}\right),$$

$$y(x) = \frac{2}{1+\sqrt{1+\left(\frac{\alpha a_0^2}{a_1}\right)^2\frac{t}{x}}}.$$

The form of the function $f_i(r, t, x)$ is such that it changes very little when the variable of integration x is varied within the limits indicated. Such modification of the function enables us to apply the mechanical quadrature formula with weight $x^{-1/2}\exp(-x)$ to (26); we can limit the number of points to two or three, obtaining

$$U(r, 0, t) = \frac{1}{\sqrt{\pi}}\sum_{k=1}^n A_c\varphi(r, t, x_c), \tag{27}$$

where $\varphi(r, t, x_\kappa) = B_1 f_1(r, t, x_\kappa) - B_2 f_2(r, t, x_\kappa)$. The numerical values of A_c and x_c depend on the number of abscissas [13].

We will now consider a specific example and establish the specific form of $\Phi(r)$, i.e., determine the values of B_1, B_2, b_1, and b_2.

Preliminary calculations show that, if 15-20 kg of magnesium is utilized for each meter of formation thickness, the average temperature of the hole bottom zone is raised by about 150-170°C from the initial formation temperature. The radius of solution penetration is of the order of 1.3 m if the porosity is m = 0.2.

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The initial temperature for $r > R_c = 1.3$ m consequently equals the original formation temperature, i.e., $T_0 - T \simeq 0$, we can now compile the necessary conditions for determination of the coefficients:

1. $\qquad\qquad\qquad\qquad\qquad B_1 - B_2 = T_c - T_0$ when $r \to 0$. $\qquad\qquad\qquad$ (28)

2. The average temperature in the hole bottom zone is:

$$\Delta T_{av} = \frac{2}{R_c^2} \int_0^{R_c} (T - T_0)\, r\,dr = \frac{B_1}{b_1 R_c^2} - \frac{B^2}{b_2 R_c^2}.$$
(29)

We assume that

$$\Delta T_{av} = 0 \text{ when } r = R_c$$
(30)

in this case.

3. The temperature distribution function has a maximum at some distance $r = r_0$, so that:

$$B_1 b_1 \exp\left(-b_1 r_0^2\right) - B_2 b_2 \exp\left(-b_2 r_0^2\right) = 0.$$
(31)

The coefficients sought are determined from Eqs. (28)-(31) on the basis of the experimental data, specifying $r = 0.3$ m, $R_c = 1.2$ m, and $T_w = T_0 = 20°C$ at $t = 0$; the initial temperature distribution function then takes the form:

$$\Phi(r) = 0.97 \exp\left(-2.78\bar{r}^2\right) - 0.77 \exp\left(-24.44\bar{r}^2\right),$$
(32)

where $r = r_0 \bar{r}$.

We obtain for the known parameters $a_0 = 3.04 \cdot 10^{-3}$ m³/h, $a_1 = 1.365 \cdot 10^{-3}$ m³/h, $r_0 = 1$ m, and $\alpha = 0.815$ m⁻¹:

$$\varphi(r, t, x_c) = \frac{0.97}{\omega_1(t,y_c)} \exp\left(-\frac{2.78\bar{r}^2}{\omega_1(t,y_c)}\right) - \frac{0.77}{\omega_2(t,y_c)} \exp\left(-\frac{24.44\bar{r}^2}{\omega_2(t,y_c)}\right),$$

$$\omega_i(t, y_c) = 1 + 4b_i a_0^2 + y_c(x),$$
(33)

$$y_c(x) = \frac{2}{1 + \sqrt{1 + 0.0045\, \dfrac{t}{x_c}}}.$$

Substituting from (33) into (27) and limiting ourselves to three terms $n = 3$ with $x_1 = 0.19016$, $A_1 = 1.4493$, $x_2 = 1.7845$, $A_2 = 0.31413$, $x_3 = 5.5253$, and $A_3 = 0.00906$ gives us the specific form of the temperature distribution equation.

Equation (27) is used to compute U as a function of r and t, and the temperature distribution curves are plotted.

Figure 3 gives plots for the dimensionless temperature versus r at different times. These curves show that, as time goes on, most of the heat obtained at $\bar{r} = 0.3$ goes to environmental heating, so that the temperature in the hole bottom zone gradually equalizes.

Figure 4 depicts temperature as a function of time for different distances from the well axis. Analysis of these curves enables us to establish the zone of thermal influence during formation thermochemical treatment as a function of the specific conditions in the hole bottom zone and the thermal effect on it.

Our research results permit correct and timely assessment of normality of operation for wells exploiting formations with hard-to-extract crudes.

NOTATION

U, V, normed temperatures; a_0, a_1, coefficients of thermal diffusivity for formation and environment; λ_0, λ_1, coefficients of thermal conductivity for formation and environment;

m, formation porosity; h, formation thickness, m; r_w, well radius, m; τ, dimensionless time; $\bar{r}$, dimensionless radius; $I_0(x)$, $K_0(x)$, zero-order Bessel functions of first and second kinds with imaginary argument; $J_0(x)$, zero-order Bessel function of first kind for real argument; LU, Laplace transformation; $\bar{U}$, $\bar{V}$, Laplace transforms of functions; S, Laplace transformation parameter; $\bar{U}$, $\bar{V}$, Hankel transforms of functions; ρ, Hankel transformation parameter; A_c, B_1, B_2, b_1, b_2, constant parameters; ρ_0, density, kg/m^3; c_0, c_1, specific heat capacities, J/(kg·deg); T_0, initial formation temperature, deg; T, current formation transformation, deg; T_w, hole bottom temperature, deg; Q, liquid volume delivery rate, m^3/sec; r_0, radius of hot front boundary, m; F, Froude number; q, amount of heat; R, profile radius; k, constant parameter.

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