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A QUASI-STATIONARY TEMPERATURE FIELD IN THE SHAFT OF AN OPERATING WELL

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Temperature fields in the shaft of an operating well are studied experimentally in a quasi-stationary approximation. The expressions for radial distributions of temperature and coefficients of heat transfer are obtained with account for the dependence of the velocity of liquid flow on the radial coordinate. Calculations are made for laminar and turbulent flows.

Study of temperature fields in liquid and gas flows in pipes is of importance for pipeline transportation of heat carriers and products. However, their investigation in shafts of oil wells is of particular significance. On the one hand, calculations of temperature fields in wells are important for prediction of paraffin deposits of the well walls; on the other hand, this problem is a basic one in thermal coring, which is widely used in practice in studying wells and beds.

Nonstationary temperature fields in the shaft of the well and the surrounding medium mutually affect each other. The equalities of temperatures and heat fluxes on pipe walls (boundary conditions of the fourth kind) are natural boundary conditions that determine this interaction. Since solution of conjugate problems presents fundamental difficulties, the problem in a precise formulation was replaced by a simpler one. The first approach was developed by V. G. Shukhov and A. Yu. Namiot [1], who suggested using the Newton formula for heat transfer on a surface and took the coefficient of heat exchange between the flow in the well and the surrounding rocks as time-independent. É. B. Chekalyuk used an integral method to take into account heat exchange between the flow and the surrounding rocks and specified heat flux in the form of convolution [2]; it is this approach within the framework of which A. N. Salamatin made his studies [3]. Other researchers [4–6] also referred to the problem under discussion, but all of them considered the problem only for a mean temperature in the well shaft. At the same time, use of thermal studies in the practice of development of oil-gas deposits aggravated the problem of calculation of radial temperature dependences in the well. This is related to the fact that a thermometer, which was run into the well on a cable along the shaft of the well and more often close to its wall, in some cases moves away from the latter, thus approaching the well axis. Therefore, it is essential to know radial temperature distributions in the flow in order to predict the thus-arising temperature anomalies. However, the study of radial temperature distributions in liquid or gas flows in the well shaft is of independent importance for development of new methods of coring based on measurements of the dependence of temperature on the distance to the well axis. However, at present there is no acceptable theory of temperature effects under these conditions.

In this paper, we made an attempt to construct a theory of thermal processes in a well on the basis of a quasi-stationary approximation that lies in the fact that the differential equations for temperature are taken to be stationary and time enters into the considered problem parametrically. It is shown that this approach allows one to develop new methods of calculation of radial temperature distributions in a flow.

In the problem it is assumed that (a) the surrounding medium is homogeneous and anisotropic, (b) the temperature of the distant parts of rocks changes with depth according to the linear law, and (c) the region of depths where seasonal oscillations of temperature on the surface do not penetrate is considered. It is taken that only the component of the velocity along the well axis differs from zero; this component depends only on the distance to the well axis $v = v(r) = v_0 \upsilon(r)$ and so on.

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Mathematical Formulation of the Problem and Its Solution. The formulation of the problem under the assumption of an axial symmetry includes the heat-conduction equation in the mass surrounding the pipe

$$\rho_1 c_1 \frac{\partial \theta_1}{\partial \tau} = \lambda_{1z} \frac{\partial^2 \theta_1}{\partial z_d^2} + \lambda_{1r} \frac{1}{r_d} \frac{\partial}{\partial r_d} \left(r_d \frac{\partial \theta_1}{\partial r_d} \right), \quad r_d > r_0 , \quad \tau > 0 , \tag{1}$$

and the equation of convective thermal conductivity of the fluid (in the general case, multiphase) with sources in the pipe

$$\rho c \frac{\partial \theta}{\partial \tau} = \frac{\partial}{\partial z_d} \left[(\lambda_z + \lambda_{zt}) \frac{\partial \theta}{\partial z_d} \right] + \frac{1}{r_d} \frac{\partial}{\partial r_d} \left[(\lambda_r + \lambda_{rt})\, r_d \frac{\partial \theta}{\partial r_d} \right] - \rho c v \frac{\partial \theta}{\partial z_d} + q_1 , \quad r_d < r_0 , \quad \tau > 0 . \tag{2}$$

The expression for the density of sources

$$q_1 = -\,\eta c \rho^2 g v_0 \upsilon (r) - \varepsilon_1 \mu c \rho v_0^2 (\upsilon'' + \upsilon' / r)\, \upsilon (r) - L \alpha_1 g \rho \rho_s v_{s0} \upsilon (r) = q_0 \upsilon (r) \tag{3}$$

includes the following terms: $-\eta c \rho^2 g v_0$ (describes an adiabatic effect in an ascending flow), $-\varepsilon_1 \mu c \rho v_0^2 \upsilon(\upsilon'' + \upsilon'/r)$ (corresponds to heat releases due to internal friction), and $-L\alpha_1 g \rho \rho_s v_{s0} \upsilon(r)$ (allows for the temperature effect of phase transitions due to liberation of the dissolved gas). At the boundary of the pipes and the surrounding mass the conditions of the equality of temperatures

$$\theta \big|_{r_d = r_0} = \theta_1 \big|_{r_d = r_0} \tag{4}$$

and heat fluxes

$$\lambda_r \frac{\partial \theta}{\partial r_d} \bigg|_{r_d = r_0} = \lambda_{1r} \frac{\partial \theta_1}{\partial r_d} \bigg|_{r_d = r_0} \tag{5}$$

are specified. For the sake of simplicity, we consider the case where the coordinate z of the vector of the temperature gradient is constant; in the literature it has the conventional name of the "case of constant gradients":

$$\frac{\partial \theta}{\partial z_d} = \frac{\partial \theta_1}{\partial z_d} = \text{const} . \tag{6}$$

This allows one to abstract oneself from the account of boundary conditions at certain values of the coordinate z; moreover, Eqs. (1) and (2) are simplified since the second derivative with respect to the coordinate z vanishes.

The boundary conditions correspond to the Earth’s natural undisturbed temperature, which increases with depth z_d according to the linear law; this temperature coincides with the temperature at the points of the surrounding mass, which lie at a distance from the pipe:

$$\theta_1 \big|_{r_d = R(\tau)} = T_{01} - \Gamma z_d . \tag{7}$$

We consider a quasi-stationary approximation that consists of the fact that the differential equations for temperature are taken to be stationary. However, time enters into the considered problem parametrically in terms of the radius of the zone of thermal effect of the well $R(\tau)$, which is determined by the method of successive change-over of stationary states. The equation for determination of $R(\tau)$ is constructed on the basis of balance relations for the amount of heat. In the problem under consideration it has the form

$$\frac{dR}{d\tau}\int\limits_{r_0}^{R}\frac{\partial\theta_1}{\partial R}\,r\,dr = -\,a_{1r}r_0\left.\frac{\partial\theta_1}{\partial r}\right|_{r=r_0},\quad R(\tau=0)=r_0\,. \tag{8}$$

The sought-for solution is superimposed by the symmetry condition that lies in the fact that the derivative with respect to the radial coordinate on the z axis (at the center of the well) vanishes.

Using the relations $r = r_d/r_0$, $R = R_d/r_0$, $T_1 = (\theta_1 - T_{01} + \Gamma z_d)/\theta_0$, $T = (\theta - T_{01} + \Gamma z_d)/\theta_0$, $t = \tau\lambda_{1r}/(\rho_1 c_1 r_0^2)$, $\gamma = r_0/D$, $\varepsilon = \lambda_{1r}/\lambda_r$, and $\chi = c_1\rho_1/(c\rho)$, we reduce problem (1)–(8) to the dimensionless form

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T_1}{\partial r}\right)=0\,, \tag{9}$$

$$\frac{\chi}{\varepsilon}\frac{1}{r}\frac{\partial}{\partial r}\left(r\Lambda(r)\frac{\partial T}{\partial r}\right)-\mathrm{Pe}\,\gamma\upsilon(r)\frac{\partial T}{\partial z}+G+q=0\,, \tag{10}$$

$$T\big|_{r=1}=T_1\big|_{r=1}\,, \tag{11}$$

$$\left.\frac{\partial T}{\partial r}\right|_{r=1}=\varepsilon\left.\frac{\partial T_1}{\partial r}\right|_{r=1}, \tag{12}$$

$$T_1\big|_{r_d=R(t)}=0\,, \tag{13}$$

where $\mathrm{Pe} = v_0r_0/a_{1r}$ is the Peclet number; $\Lambda(r) = 1+\lambda_{rt}(r)/\lambda_r$, $G = \Gamma v r_0^2/(a_{1r}\theta_0) = \mathrm{Pe}\gamma\Gamma D\upsilon(r)/\theta_0$, $q = r_0^2 q_0\upsilon\times$ $\times(r)/(c\rho\theta_0 a_{1r}) = -\mathrm{Pe}\,\gamma\Gamma D\delta\upsilon(r)/\theta_0$, $\delta = \eta\rho g + \varepsilon_1\mu v_0(\upsilon'' + \upsilon'/r) + L\alpha g\rho_s v_{s0}/(cv_0))/\Gamma$, and $q_0 = -(\eta c\rho^2 g v_0 + \varepsilon_1\mu c\rho v_0^2\times$ $\times(\upsilon''+\upsilon'/r) + L\alpha g\rho\rho_s v_{s0})$. It follows from these formulas that it is expedient to take ΓD as θ_0. The equation for the dimensionless radius of the zone of thermal effect of the well $R(\tau)$ is represented as

$$\frac{dR}{dt}\int\limits_{1}^{R}\frac{\partial T_1}{\partial R}\,r'dr' = -\left.\frac{\partial T_1}{\partial r}\right|_{r=1},\quad R(t=0)=1\,. \tag{14}$$

By virtue of the theorem on maximum and minimum values of the solutions of Eqs. (9) and (10) and with account for condition (13) we can easily find that the derivative with respect to z of the sought-for solution is zero in both regions if the density of sources does not depend on the vertical coordinate. Therefore, the problem solution is constructed provided that

$$\frac{\partial T_1}{\partial z}=\frac{\partial T}{\partial z}=0\,. \tag{15}$$

The analytical solution of the problem is constructed in this formation. Solution of Eq. (9) with account for condition (11) is presented in the form

$$T_1 = -\,T(r=1)\,\frac{\ln(r/R)}{\ln(R)}\,, \tag{16}$$

and that of Eq. (10) with account for condition (15) as

$$T = T\,(r = 1) - \varepsilon\,(1 - \delta)\,\frac{\mathrm{Pe}\,\gamma\Gamma D}{\chi\theta_0}\int\limits_1^r \frac{dy}{y\Lambda\,(y)}\int\limits_0^y r'\upsilon\,(r')\,dr' \,. \tag{17}$$

It follows from the obtained expression that the difference of temperatures between any point of the well and the wall does not depend on time. The value of the temperature at the boundary $T(1) = T(r = 1)$ is determined from the boundary condition (12) after substitution of relations (16) and (17) into it:

$$T\,(r = 1) = (1 - \delta)\,\frac{\mathrm{Pe}\,\gamma\Gamma D}{\chi\theta_0}\,\ln\,(R)\int\limits_0^1 r'\upsilon\,(r')\,dr' \,. \tag{18}$$

The expression for temperature in the surrounding medium (16) after substitution of (18) into it takes on the form

$$T_1 = (1 - \delta)\,\frac{\mathrm{Pe}\,\gamma\Gamma D}{\chi\theta_0}\int\limits_0^1 r'\upsilon\,(r')\,dr'\,\ln\left(\frac{R}{r}\right), \quad 1 < r < R\,(t)\,, \tag{19}$$

and in the well (17) becomes

$$T_1 = (1 - \delta)\,\frac{\mathrm{Pe}\,\gamma\Gamma D}{\chi\theta_0}\left[\ln\,(R)\int\limits_0^1 r'\upsilon\,(r')\,dr' + \varepsilon\int\limits_r^1 \frac{dy}{y\Lambda\,(y)}\int\limits_0^y r'\upsilon\,(r')\,dr'\right], \quad r < 1\,. \tag{20}$$

The expression for the radius of the zone of thermal effect of the well $R = R(t)$, which enters into (19) and (20), is determined from (14) after substitution of (19) into it. Solution of the thus-obtained differential equation leads to an implicit dependence of the radius of the zone of thermal effect of the well on time:

$$R^2 - 2\ln R = 1 + 4t\,. \tag{21}$$

Expressions (19)–(21) are the unknown solution of problem (9)–(14) for an arbitrary velocity distribution $v = v_0\upsilon(r)$. We note that if v_0 is the mean velocity, then the integral $\int\limits_0^1 r'\upsilon(r')dr'$ in (19) and (20) and in what follows must be replaced by its exact value 1/2.

The heat-transfer coefficient is determined as the ratio of the heat flux through the unit length surface of the pipe to the mass-mean (over the pipe cross section) value of temperature; then, with account for (19) and (20), we have

$$k = -\frac{2\pi\lambda_{1r}}{\langle T\rangle}\frac{\partial T_1}{\partial r}\bigg|_{r=1} = 2\pi\lambda_{1r}\left[\ln\,(R) + \varepsilon\left(\int\limits_0^1 r'\upsilon\,(r')\,dr'\right)^{-2}\int\limits_0^1 r\upsilon\,(r)\,dr\int\limits_r^1 \frac{dy}{y\Lambda\,(y)}\int\limits_0^y r'\upsilon\,(r')\,dr'\right]^{-1} . \tag{22}$$

The thus-determined heat-transfer coefficient differs from the coefficient of heat transfer

$$\alpha = -\frac{\lambda_{1r}/r_0}{\langle T\rangle - T\,(1)}\frac{\partial T_1}{\partial r}\bigg|_{r=1} = \frac{\lambda_r}{r_0}\left(\int\limits_0^1 r'\upsilon\,(r')\,dr'\right)^2\left[\int\limits_0^1 r\upsilon\,(r)\,dr\int\limits_r^1 \frac{dy}{y\Lambda\,(y)}\int\limits_0^y r'\upsilon\,(r')\,dr'\right]^{-1} , \tag{23}$$

which in the problem under consideration does not depend on time, since (23) does not include $R(t)$.

Partial Cases. The obtained solution allows one to construct computational relations for temperature fields of laminar and turbulent flows. If the velocity and thermal diffusivity in a pipe do not depend on the radial coordinate, we have

$$\upsilon(r) = 1\,, \quad \Lambda = 1\,. \tag{24}$$

Substitution of (24) into (19) and (20) allows one to transform them as

$$T = (1-\delta)\,\frac{\mathrm{Pe}\,\gamma\Gamma D}{2\chi\theta_0}\left[\ln R + \frac{\varepsilon}{2}(1-r^2)\right], \quad r < 1\,, \tag{25}$$

$$T_1 = (1-\delta)\,\frac{\mathrm{Pe}\,\gamma\Gamma D}{2\chi\theta_0}\ln\left(\frac{R}{r}\right), \quad 1 < r < R(t)\,. \tag{26}$$

Since v_0 is an averaged velocity, the mass-mean value of temperature in the well in the case of a constant velocity profile has the form

$$\langle T\rangle = (1-\delta)\,\frac{\mathrm{Pe}\,\gamma\Gamma D}{2\chi\theta_0}\left(\ln(R) + 4\varepsilon\int_0^1 r\upsilon(r)\,dr\int_r^1\frac{dy}{y\Lambda(y)}\int_0^y r'\upsilon(r')\,dr'\right) = (1-\delta)\,\frac{\mathrm{Pe}\,\gamma\Gamma D}{2\chi\theta_0}\left(\ln R + \frac{\varepsilon}{4}\right), \tag{27}$$

and the expression for the heat-transfer coefficient is

$$k_{\mathrm{v}} = \frac{8\pi\lambda_{1r}}{\varepsilon + 4\ln R} \tag{28}$$

and in combination with (21) it determines the dependence of k_{v} on time. In this case, the heat-transfer coefficient is determined by the following simple expression: $\alpha = 4\lambda_r/r_0$. According to (25), the difference of temperatures between the wall and the well center does not depend on time and the well radius; it is proportional to the output of the fluid Q and the geothermal gradient Γ and is in inverse proportion to the coefficient of thermal diffusivity a_r:

$$\Delta\theta_{\mathrm{v}} = \frac{v_0 r_0^2\Gamma}{4a_r}(1-\delta) = \frac{Q\Gamma}{4\pi a_r}(1-\delta)\,. \tag{29}$$

For a *laminar flow*, the velocity distribution in the pipe is a parabola and the turbulent component of thermal conductivity is absent; therefore

$$\upsilon(r) = 2(1-r^2)\,, \quad \Lambda = 1\,. \tag{30}$$

Substitution of (30) in (19) and (20) allows one to transform them as

$$T = \frac{\mathrm{Pe}\,\gamma\Gamma D}{2\chi\theta_0}(1-\delta)\left[\ln R + \frac{\varepsilon}{4}(3 + r^4 - 4r^2)\right], \quad r < 1\,, \tag{31}$$

$$T_1 = \frac{\mathrm{Pe}\,\gamma\Gamma D}{2\chi\theta_0}(1-\delta)\ln\left(\frac{R}{r}\right), \quad 1 < r < R(t)\,. \tag{32}$$

The mass-mean value of temperature in the well in the case of a laminar flow has the form

$$\langle T\rangle = \frac{\mathrm{Pe}\,\gamma\Gamma D}{2\chi\theta_0}(1-\delta)\left(\ln R + \frac{11\varepsilon}{24}\right), \tag{33}$$

and the expression for the heat-transfer coefficient

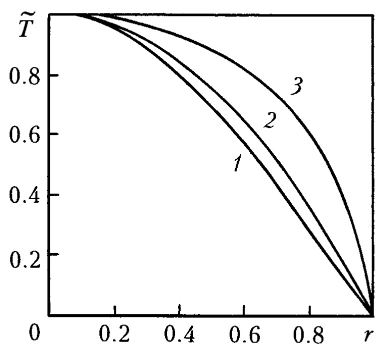


Fig. 1. Dependence of the relative temperature on the radius: 1) laminar flow; 2) constant velocity; 3) turbulent flow.

$$k_{\text{lam}} = \frac{48\pi\lambda_{1r}}{11\varepsilon + 24 \ln R} \tag{34}$$

in combination with (21) determines the dependence of this coefficient on time for a laminar flow. In this case, the heat-transfer coefficient is determined by the following simple expression: $\alpha = 24\lambda_r/(11r_0)$, which coincides with that found in [7]. The difference of temperatures between the wall and the well center in a laminar flow is 1.5 times greater than in the previous case and differs only by the factor

$$\Delta\theta_{\text{lam}} = \frac{3v_0 r_0^2 \Gamma}{8a_r}(1 - \delta) = \frac{3Q\Gamma}{8\pi a_r}(1 - \delta) . \tag{35}$$

Calculations for a *turbulent flow* in the pipe are made by the implicit Spalding equation for velocity distribution [7]

$$y_1 = u + \frac{1}{E}\left[\exp(\kappa u) - 1 - \kappa u - \frac{(\kappa u)^2}{2} - \frac{(\kappa u)^3}{6} - \frac{(\kappa u)^4}{24}\right] \tag{36}$$

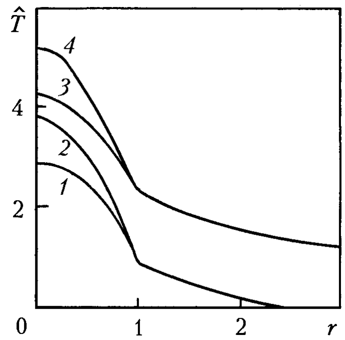
and thermal conductivity with account for the turbulent component

$$\Lambda = 1 + \frac{\kappa}{E}\left[\exp(\kappa u) - 1 - \kappa u - \frac{(\kappa u)^2}{2} - \frac{(\kappa u)^3}{6}\right], \tag{37}$$

where $y_1 = (1 - r)r_0\sqrt{\tau_0\rho}/\mu$, $u = v_0/\sqrt{\tau_0/\rho}$, $\kappa = 0.407$, and $E = 10$.

Discussion of the Calculation Results. Figure 1 presents the radial dependences of the relative temperature difference between the wall and the points inside the well $\tilde{T} = (T(r) - T(1))/(T(0) - T(1))$, $T(0) = T(r = 0)$, and $T(1) = T(r = 1)$. We note that this parameter does not depend on the geothermal gradient and is determined only by the velocity (and thermal conductivity) field of the liquid in the flow. It follows from the figure that the temperature profile is more leveled at the center of the turbulent flow (curve 3), and in this case, maximum values of the gradient are observed in the zone close to the wall. The turbulent component of thermal conductivity is the main reason for this leveling. The velocity profile slightly affects radial distributions of the relative temperature. This can be checked by comparison of curves 1 and 2 calculated for a laminar flow and the hypothetical case of constant velocity over the flow cross section, respectively; these curves turn out to be unexpectedly close. We note that absolute values of the differences of temperature between the wall and the well axis are maximum for a laminar flow and minimum for a turbulent flow.

Figure 2 shows a comparison of the relative temperature $\hat{T} = T2\chi\theta_0/(\text{Pe}\ \gamma\Gamma D)$ for a laminar flow and the hypothetical case of constant velocity over the flow cross section depending on the radial coordinate in the well and the surrounding rocks. In the calculations we took $\varepsilon = 4$. Comparison of curves 1 and 2 calculated for dimensionless time



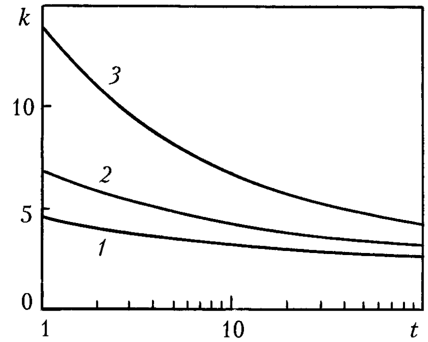


Fig. 2. Dependence of the relative temperature on the radius at different values of dimensionless time [1, 2) t = 1; 3, 4) 20]: 1, 3) constant velocity; 2, 4) laminar flow.

Fig. 3. Dependence of the heat-transfer coefficient on time: 1–3) for the notation see Fig. 1.

t = 1 and curves 3 and 4 for t = 20 indicates the increase in the relative temperature with time. Values of the relative temperature in the hypothetical case of constant velocity (curves 1 and 3) in the well are lower than in a laminar flow (curves 2 and 4). It follows from the figure that in the two cases the temperature fields in the surrounding mass coincide.

Figure 3 presents the results of calculation of the heat-transfer coefficient for laminar and turbulent flows and the hypothetical case of constant velocity over the flow cross section as a function of time. In the calculations, the thermal conductivity of the surrounding mass is taken to be λ = 2 W/(m·K). Values of the heat-transfer coefficient are minimum for a laminar flow and maximum for a turbulent flow.

We note that the quasi-stationary approximation used allowed construction of the relations that are essential for calculation of the temperature fields in the wells and, in particular, for the radial distributions of temperature of laminar and turbulent flows.

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NOTATION

a_r and a_{1r}, coefficients of radial thermal diffusivity of the fluid and the surrounding rocks, respectively, m^2/sec; c and c_1, specific heat capacity of the fluid and the surrounding rocks, respectively, J/(K·kg); D, depth of the well, m; g, free-fall acceleration, m/sec^2; k, coefficient of heat transfer in the well, W/(m·K); L, heat of phase transition, J/kg; Q, output of the well, m^3/sec; r_d, z_d and r, z, dimensional and dimensionless cylindrical coordinates, respectively, m; r_0, well radius, m; R, radius of the zone of thermal effect of the well, m; T, dimensionless temperature of the fluid; T_1, dimensionless temperature of the mass; T_{01}, natural temperature in the plane z = 0, K; y, integration variable; v, velocity of liquid in the pipe, m/sec; v_0, mean velocity of liquid, m/sec; v_{s0}, mean velocity of liquid at saturation pressure, m/sec; α, heat-transfer coefficient, W/(m^2·K); α_1, coefficient of gas solubility, 1/Pa; Γ, geothermal gradient, K/m; ε_1, Joule–Thomson coefficient, K/Pa; η, adiabatic coefficient, K/Pa; θ, temperature of the fluid, K; θ_1, temperature of the surrounding bed, K; λ_r and λ_z, coefficients of thermal conductivity of flow along the axes r and z, W/(m·K); λ_{1r} and λ_{1z}, coefficients of thermal conductivity along the axes r and z in the bed, W/(m·K); μ, viscosity, Pa·sec; $\upsilon(r)$, function of radial velocity distribution; ρ and ρ_1, densities of the fluid and the surrounding rocks, respectively, kg/m^3; ρ_s, density of the fluid at pressure of saturation, kg/m^3; τ and t, dimensional and dimensionless time, sec; τ_0, stress, Pa. Indices: v, leveled velocity profile; d, dimensional; lam, laminar; s, gas saturation; t, turbulent.

REFERENCES

1. A. Yu. Namiot, Temperature variation along the shaft of operating wells, *Neft. Khoz.*, No. 5, 45–48 (1955).

2. É. B. Chekalyuk, *Thermodynamics of the Oil-Bearing Bed* [in Russian], Nedra, Moscow (1965).
3. M. A. Pudovkin, A. N. Salamatin, and V. A. Chugunov, *Temperature Processes in Operating Wells* [in Russian], Izd. Kazan. Univ., Kazan' (1977).
4. A. I. Filippov, *Well Thermometry of Transient Processes* [in Russian], Izd. Saratov. Univ., Saratov (1989).
5. A. I. Filippov, The theory of heat exchange of a liquid flow in a well in compression testing, development, and sampling, *Izv. Vyssh. Uchebn. Zaved., Neft' Gaz*, No. 12, 60–65 (1986).
6. H. D. Murphy, Enhanced interpretation of temperature surveys taken during injection or production, *J. Petrol. Technol.*, **34**, No. 6, 1313—1326 (1982).
7. W. M. Kays, *Convective Heat and Mass Transfer* [Russian translation], Énergiya, Moscow (1972).